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Design, construction, and operation of water treatment plant residual monofills

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ABSTRACT

DESIGN, CONSTRUCTION, AND OPERATION OF WATER TREATMENT PLANT RESIDUAL MONOFILLS

by
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Due to the stringent environmental regulations, landfilling becomes the most viable option for ultimate disposal of water treatment plant (WTP) residues. At present, most states apply the regulations for municipal solid waste (MSW) landfills to the landfilling of WTP residues. This is too stringent since the WTP residues are not hazardous. Therefore, development of suitable criteria for WTP residual monofills is necessary and urgent.

A set of environmental and geotechnical experiments was conducted to characterize WTP residues. It can be concluded that very little leachate will be produced and migration of leachate is unlikely. Also it was noted that insignificant amounts of biogas were produced in the tests conducted.

Based on the investigations, it was observed that criteria applicable to MSW landfills regarding liners, leachate and groundwater monitoring systems and gas venting systems can be modified suitably for application to WTP monofills.

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by
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CHAPTER 1

INTRODUCTION

1.1 General

The water treatment plant (WTP) residual monofill is a specific landfill that accepts only WTP residues. It serves all the functions of an ordinary landfill while minimizing disposal costs. Emergence of WTP residual monofill is due to the stringent environmental regulations regarding the possible means of disposal and economic considerations (Hsieh and Raghu, 1991).

Several million tons of solids are produced by water treatment plants every year. How and where to ultimately dispose of this large amount of WTP residues are always problems to these water treatment plants. In the past, WTP residues were discharged into sanitary sewers, streams, or oceans, or dumped into municipal solid waste landfills. However, these traditional disposal methods have encountered difficulties now. Discharging of residues into the sewer should fulfill the pretreatment standards set up by waste water treatment plants according to the Clean Water Act (CWA). Under National Pollutant Discharge Elimination System (NPDES), a permit must be obtained to discharge WTP residues into any water body.

Landfills are always a part of the disposal hierarchy and are probably the most cost-effective ones now.(Kelly,

1990) However, no specific regulation exists regarding WTP residual landfills. Most states treat WTP residues along with other municipal solid wastes as far as landfill regulations are concerned and allow these residues to be dumped into same landfills. Under these circumstances, some severe liability problems may occur. According to Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), if a water treatment plant disposed of its residues at a landfill that also accepted other waste that contaminated the groundwater or soil, the water treatment plant could be liable for cleanup based on its use of the landfill. This is so, even if the WTP residue did not at all contribute to contamination.

Moreover, the Subtitle D of the new Resource Conservation and Recovery Act (RCRA) that stipulates quite stringent criteria for Municipal Solid Waste (MSW) Landfills went into effect on October 9, 1993. It would be unrealistic and uneconomical if these criteria were to be applied to WTP residual monofills. This is due to the fact that the WTP residues are relatively homogeneous and impervious as compared with MSW. Consequently, the monofill for ultimate disposal of WTP residues will become a future trend, and development of suitable and realistic criteria for design, construction and operation of WTP residual monofills is necessary and urgently needed (Raghu, Hsieh, and Bian, 1993).

1.2 Scope and Objective of Research

The objective of this research is to determine the environmental and geotechnical characteristics of water treatment residues, and finally develop criteria for the WTP residual monofills.

This investigation is divided into four parts:

(1) To test different types of water treatment plant residue samples,

(2) To characterize the geotechnical and environmental properties of WTP residues based on the experimental investigations and relevant information from other sources,

(3) To research the existing criteria related to WTP residual monofills, and

(4) To develop criteria for WTP residual monofills.

1.3 The Structure of the Thesis

In the following chapter, a literature survey regarding the historic regulations related to the disposal of the WTP residue will be presented. Production and properties of the WTP residues and existing criteria influencing WTP residual disposal will also be reviewed in the second chapter.

A brief introduction of the environmental and geotechnical experimental methods used in this research is presented in chapter 3.

In chapter 4, the environmental and geotechnical characteristics of WTP residues based on the results of this research are discussed.

Chapter 5 is the major part of this thesis. The criteria for planning, designing, constructing and operating WTP residual monofills are proposed. A short discussion on cost analysis also included in this chapter.

The last chapter of this thesis is devoted to summary and a short discussion of future research that need to be carried out to develop a final criteria for WTP residual monofills.

CHAPTER 2

LITERATURE SURVEY

Relevant literature regarding the disposal criteria of WTP residues is extremely limited. In this thesis, a brief historical review of the applicable regulations will be performed. Then the literature regarding properties and production of WTP residues will be discussed followed by a review of the existing criteria related to the WTP residual monofills.

2.1 General

In 1953, a status report on state regulations concerning water treatment plant wastes revealed that only five states considered their discharges violating regulations (Dean, 1953), and from then on, rapid changes began to occur in this field. Passage of PL 84-660, Water Pollution Control Act in 1965, required states to set standards for interstate waters and gave them authority to order treatment of wastes from water treatment plants before discharge to surface waters.

AWWA Research Foundation issued a report in 1969 on the disposal of wastes from water treatment plants. Then, only five states had no laws regulating water treatment plant waste disposal (AWWA Research Foundation, 1969). However, little attention was paid to disposal operation because residue treatment facilities were not required to monitor the treatment efficiency of disposal at that time.

Until 1972, the problem of disposal of water treatment plant residues received considerable attention since the publication of a report of the Disposal of Water Treatment Plant Wastes Committee (1972). The report reviewed the procedures used for reclaiming, processing, and disposing of the water treatment plant residues and discussed the current technology and future investigations. Due to this report, Public Law 92-500, the Water Pollution Control Act Amendments of 1972 were promulgated which classified water treatment residues as industrial wastes and required to comply with the provisions of the act.

The Resource Conservation and Recovery Act (RCRA) was enacted into law by the US. Congress in 1976. It was amended in 1984, and established the basis for US Subtitle D of RCRA that deals with waste treatment, storage, and disposal (AWWA Committee Report, 1978). On October 9, 1993, new RCRA Subtitle D regulations went into effect. These regulations have prompted the state regulatory agencies to update their requirements regarding solid waste disposal.

2.2 Production and Properties of WTP Residues

WTP residues are produced from water treatment processes such as softening, coagulation, and filtration, during the removal of impurities such as sand, silt, clay, organic, ions from water. Properties of these residues vary from plant to plant, and even in the same plant from time to time. They depend upon the water quality, the water treatment processes and the chemical additives used in the process (AWWA Committee Report, 1978).

Lime is the most common softener used process to reduce hardness of water. Part of the calcium and magnesium present in the raw water is removed during this process. Residue produced consists mainly of calcium carbonate with other components such as magnesium hydroxide, silt, and minor amounts of lime and organic matter. Softening residues tend to be thixotropic. This sludge is allowed to settle. The solid content of settled sludge varies from 2 to 30 percent (AWWA Committee Report, 1978).

Coagulation and subsequent flocculation are employed in water treatment processes for removing silt, dissolved or colloidal organic material, microscopic organisms, and colloidal metallic hydroxides. Sulfate of alumna (alum) is the primary coagulant used. Other chemicals, such as lime polymer, activated carbon, or activated silica may also be used. Major components of the coagulation residues are hydrous oxide of the coagulant and materials removed from the raw water. Coagulated residues are also thixotropic. The solids contents of these residues range between 0.1 and 3.5 percent (AWWA Committee Report, 1978).

The filtration process removes suspended matters, such as silts, hydrous oxides, clay colloids, algae, bacteria, and virus, by passing the water through a porous medium.

Materials removed by filtration are periodically cleaned from the filters by backwashing. A coagulant aid such as a polyelectrolyte may be needed to let filter residue settle (AWWA Committee Report, 1978).

2.3 Existing Criteria for Landfills

At present, the criteria controlling water treatment plant residual landfills is the revised Municipal Solid Waste Landfill (MSWLF) Criteria, promulgated on October 9 1991 in Part 258, of the Code of Federal Regulations (CFR). These criteria were promulgated by United States Environmental Protection Agency (USEPA) under the authority of both the Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, and Section 405 of the clean Water Act (CWA) on October 9, 1991

The USEPA established Draft Technical Manual for Solid Waste Disposal Facility Criteria-40 CFR Part 258 in 1991 to provide minimum national criteria for all solid waste landfills, and this criteria became effective on October 9, 1993. Owners and/or operators of MSWLFs that do not meet the above criteria will be considered to be engaging in the practice of "open dumping" in violation of Section 4004 of RCRA (40 CFR Part 258, 1992).

Also the criteria required design of new landfill or lateral expansions of existing landfills to comply with either a design standard or performance standard (40 CFR Part 258, 1992). In the criteria, a series of operating requirements pertaining to routine operation, management, and monitoring at a municipal solid waste landfill have been developed to ensure the safe daily operation of the monofill.

The state of Pennsylvania is the only state in the United States that has criteria specifically related to the WTP residual landfill. The criteria classified the WTP residue as the class III materials (Commonwealth of Pennsylvania, 1991). The class III residual waste landfills involve the disposal of residual wastes with the least degree of potential for adverse effects on groundwater and the least potential impact on public health, safety and the environment.

CHAPTER 3

MATERIALS AND EXPERIMENTAL METHODS

3.1 Introduction

In order to develop criteria for WTP residual monofills, environmental and geotechnical characteristics of WTP residues should be investigated. The materials and experimental methods employed for this purpose are discussed in this chapter.

Samples were collected from different water treatment plants. The relevant information regarding residues and plants is summarized in Table 1 in Appendix A. The tested samples can be classified in three broad categories: alum residues, lime residues, and ferric residues. Testing methods and instruments employed are listed in Table 2 in Appendix A.

3.2 Environmental Experiments

Tests conducted under this category include paint filter test, cation exchange capacity test, and Toxicity Characteristic Leaching Procedure (TCLP) test. All these tests were conducted according to the relevant Environmental Protection Agency (EPA) procedures. Details regarding these procedures, such as sampling protocols and quality assurance and quality control (QA/QC) can be found elsewhere (Tian, 1993).

Paint filter liquid test, USEPA method 9095 (USEPA, 1986), can be performed by placing 100 grams of dewatered WTP residues in a funnel that holds a filter with mesh size 60 to determine whether dewatered residues contain freely flowing water. If any liquid passes through the filter during a 5-minute period, the WTP residual is considered to contain freely flowing water. In such a case, landfills will not accept residues for disposal.

Chemical tests include determination of pH value method, USEPA method 9045 (USEPA, 1986), solid concentration, (Standard Methods, 1986), volatile solids, fixed solids, and primary metals extracted from WTP residues.

Cation exchange capacity, USEPA method 9080 (USEPA, 1986), is defined as the number of milliequivalent (meq) of the cations that 100 grams of sample will absorb. A residue with high CEC can retain ions such as calcium and aluminum on its surface. TCLP test, USEPA method 1311 (USEPA, 1986), was used to determine the mobility of both organic and inorganic contaminants in liquid, solid, and multiphase wastes. The residues were analyzed to determine the presence of 39 regulated chemical contaminants.

3.3 Geotechnical Experiments

Tests conducted under this category include water content determination tests, specific gravity of solid tests, compaction tests, direct shear tests, unconfined compression tests, consolidation tests, freeze/thaw tests, and dry/wet tests. All these tests were conducted according to the procedures set up by the American Society for Testing and Materials (ASTM).

Water content test, ASTM D 2216-90 (ASTM, 1992), is a routine laboratory test to determine the amount of water present in a quantity of soil in terms of its dry mass. Many soil properties, such as compactibility and unconfined compression strength are related to water content.

Sieve, ASTM D 421 (ASTM, 1992), and hydrometer analyses tests, ASTM D 422 (ASTM, 1992), were used to determine solid size distribution. In the tests, more than 95% of materials of water treatment residue sample passed through the No. 200 sieve (0.075 mm), so the sieve analysis was considered unnecessary for this project. Hydrometer tests were not applicable to most of water treatment residues because of the diffused double layer (DDL) and high viscosity of gel material in the residues prevented settling of particles (Hsieh and Raghu, 1992).

WTP residues contain organic materials. Heating can decompose these materials, resulting in loss of solids. Weight loss observation tests were performed to verify that the methods of drying employed did not significantly affect the solid contents of the samples after drying.

Compaction tests, ASTM D 698 (ASTM, 1992), were used to determine the optimum moisture content, which occurs at maximum dry density. Optimum moisture content is one of the most important parameters in compacting materials in field. In this research, compaction tests were performed from both dry and wet sides.

In the case of compaction tests for soils, it is common practice to dry the soil and then perform compaction tests with increasing moisture contents by adding water. This is referred to as the compaction test from the dry side. On the other hand, if a compaction test is performed at a high moisture content at first and then subsequent tests were conducted at decreasing moisture contents by air drying, then the test are supposed to be conducted from the wet side. For soils, it does not matter as to whether the test is done from the dry side or from the wet side. The results obtained are the same in both cases. But for the WTP residues, results from tests from the dry side are not the same as those from the wet side. This is due to the change in structure of residues upon drying (Xia, 1993).

The compaction tests from wet side were performed on natural residue samples. Some samples with high water contents were air dried until tests could be performed. Compaction tests from dry side were conducted after the water treatment residue samples were oven dried under a temperature of 105^0C.

Liquid limit and plastic limit tests, ASTM D 4318 (ASTM, 1992), were performed on WTP residues. These limits (sometimes called "Atterberg Limits") are used for identification and classification purposes and for correlation of certain soil properties.

The specific gravity, ASTM D 854 (ASTM, 1992), of solids is defined as the unit weight of the particle divided by the unit weight of distilled water at 4^0C. This is a basic parameter that indirectly indicates the material chemistry of the solid particles in the WTP residues.

Freeze/thaw tests, ASTM D 560 (ASTM, 1992), were conducted to determine the stability of the residues under the cycles of freezing and thawing. This property is very helpful for understanding as to how the properties of WTP residues in monofills will change through winter and summer cycles.

Wet/dry tests, ASTM D 559 (ASTM, 1992), were conducted to investigate the durability of the WTP residues in monofills which would be subjected to alternate wetting and drying.

Direct shear test, ASTM D 3080 (ASTM, 1992), is used to investigate the shear strength parameters such as cohesion and friction angle. These parameters are extremely important to predict the bearing capacity and slope stability.

Unconfined compression test, ASTM D 2166 (ASTM, 1992), is used for determining the undrained shear strength of residue. Tests were conducted at different solid contents to investigate the effects of drying and aging. Results of these tests have been used to estimate the handling characteristics of residues. For example, the minimum solid content of residue at which compacting equipment can be supported can be estimated. Relevant analyses have been presented elsewhere in this thesis.

Permeability is a critical parameter in design and operation of WTP residual monofills. Consolidation tests, ASTM D 2435 (ASTM, 1992), were performed to obtain coefficient of permeability, preconsolidation pressure, compression index, and swell index. Samples were tested at their natural water contents. Permeability was estimated based on the time-settlement curve under the first loading increment. From the results of consolidation test, settlement characteristics of WTP residues such as, primary settlement, secondary settlement, and time-rate of settlement can be evaluated.

CHAPTER 4

CHARACTERISTICS OF WTP RESIDUES

4.1 General

An evaluation of characteristic of WTP residues is essential for developing criteria for design, construction, and operation of WTP monofills. WTP residues are often characterized by high water content (low solids content), high resistance to mechanical or gravity dewatering, and other problems associated with their handling and ultimate disposal (Knocke, et al. 1983). Major components of WTP residues are soil particles, chemicals, organic materials, and water. Their source is the suspended particles and organic materials from raw water, and the chemicals added during water treatment process.

Inorganic solids are mainly clay fraction soil particles with sizes from 1nm (1nm = 10^{-6} mm) to 1 μm (1 μm = 10^{-3} mm) (Bohn et al. 1985). The carbonate, sulfur minerals, layer silicates, and various oxides are most commonly present in the clay fraction in soils. These solids usually do not take part or involve in any chemical reactions during water treatment processes (Hsieh and Raghu, 1993c).

Main Organic materials are colloidal polymers called humus that are produced by the degradation of nonhumus materials. Humus is a complex mixture that can hold large amounts of water. It tends to increase the cation exchange capacity of the residues (Hsieh and Raghu, 1993b).

Lime, alum, and ferric sulfate are commonly used chemicals in the water treatment process. Lime is usually added as a softener; alum and ferric sulfate act as coagulants.

Water treatment residues usually have high water contents. Water in the residues can be classified into four types: free water, floc water, capillary water, and bound water (Knocke et al. 1983). Change in water content of the residues is the greatest single cause of variation in the geotechnical properties. This change could be brought about by aging and removal of floc water resulting from the change in structure of residues.

4.2 Environmental Characteristics

Environmental characteristics of water treatment plant residues primarily depend upon the water source, water quality, water treatment process, and dewatering methods. Physical and chemical characteristics of dewatered residues are related to the types of conditioning agents, coagulants, dewatering equipment, and dewatering methods employed. Laboratory tests were conducted to determine solid concentrations, volatile solid contends, pH, cation exchange capacity, biodegradation, metal composition, pesticides and herbicides contents, and volatile organic compounds in the WTP residual samples.

It would become very difficult to operate a WTP residual landfill if solids content of the dewatered water treatment residues falls below 15% (Tian, 1993). This is probably based on the criteria of passing paint filter tests. In this study, the solids content of samples from dewatered water treatment residues tested varied from 15% to 60% for dewatered residue (see Table 3 in Appendix A) .

For water treatment residues, if conditioning agents are not added in processes such as in lagoons and drying beds, the pH is normally neutral. If lime is added as a conditioning agent in the processes, pH value would rise, and would range among 9 and 11. The pH of most of the water treatment residue samples tested are above 6 (see Table 3 in Appendix A). Hence these residues can be characterized as neutral to basic (alkaline), based on the pH values.

Cation exchange capacity (CEC) represents the potential ability to maintain contaminants in the waste. The CEC of majority of dewatered water treatment residues is from 50 to 130 meq/100g (see Table 3 in Appendix A). These values are higher than the CEC of soil that is about 10-40. It could be due to the small particle sizes of the residues and their high organic contents and large surface charges (Tian, 1993).

The CEC characteristics along with the pH values indicate that water treatment residues have high potential to maintain heavy metals in the residues. Hence, it is quite unlikely that metals such as aluminum and iron present in these residues will be leached out of the WTP residual monofills during the life time. Based on this information, it has been decided that the clay liner may not be required, and only a geotextile liner will be enough for containing the contaminants from the leachate out of the monofill. However, if the pH value of the residues in monofills becomes acidic due to events such as acid rains, there is a possibility of leaching of metals. It is believed that such a condition could be prevented from occurring by providing proper drainage for run-off into the monofill, and minimizing the infiltration into the monofill by a suitable final cover, impervious geotextile around the perimeter of the monofill, and drainage system inside in the monofill.

Volatile solids indicate the magnitude of the organic contents in the water treatment residues which is dependent on the properties of water sources. In this investigation, greater organic concentrations were observed in WTP residues produced by the treatment of water from reservoir than those from river (see Table 4 in Appendix A).

Experiments were conducted for evaluating the biodegradability of WTP residues. There was no biogas produced from dewatered residues when lime is used as coagulants under anaerobic conditions. This could be attributed to the high pH and alkalinity and low organic contents of WTP residues(Tian, 1993). Based on this information, it can be concluded that the gas venting systems are not necessary for lime residual WTP monofills.

TCLP tests were conducted on the water treatment residue samples, and the test results (see Table 5 in Appendix A) showed that there were no regulated toxic contaminants detected by the relevant analytical equipments and testing methods. Base on these results, it can be deduced that the leachate produced, if any, from the monofill, does not contain any toxic and/or hazardous compounds. This information reinforces the author's statement in the previous section regarding the omission of clay liners in the monofills.

4.3 Geotechnical Characteristics

Geotechnical properties of water treatment plant residues are related to physical and chemical nature of its solid and fluid components. When water content and structure of the solids change due to aging of residues in the monofills, interactions between the solid and liquid phases such as cementation take place (Xia, 1993). These will greatly affect the geotechnical properties such as compaction, shear strength, permeability and durability under weather conditions.

Water contents of water treatment residues tested for this project varied largely due to the different water sources, water treatment processes, and dewatering methods. These contents ranged from 40% to 550% in this research. Water present in the WTP residues directly influences the operation of WTP residual monofills. The dramatically varying water content may cause some difficulties in compaction especially when the residues are too wet to compact.

Compactibility of water treatment residues is extremely important in operating WTP residual monofills. For the purpose of the developing the criteria, it is more realistic to use the results of the compaction test from wet side. However, if the landfilling operation involve compaction of dried and/or dry residues, results from tests from dry side test can be used to provide the required criteria for compaction such as optimum moisture contents and maximum dry densities.

When residue samples were tested from wet side, many of them behaved just like soils, exhibiting one hump with a well-defined peak for water content vs. dry density curves (see Figure 1 in Appendix B). But for some of the residue samples, the dry density kept on increasing with decreasing moisture content (see Figure 2 in Appendix B). In the tests from dry side, all residue samples exhibited one hump curves with a peak (see Figure 3 in Appendix B).

Compaction characteristics have to be taken into account in WTP residual monofill operations. If a WTP residual monofill accepts several different types of residues, it is difficult to achieve adequate compaction of residues with low solid contents, since they have different optimum moisture contents. It is also observed that the maximum dry density from dry side is higher than that from the wet side. This property may be attributed to the thixotropic hardening and cementation developing in the residues (Xia, 1993). In such cases, the residues should be air dried for a period of time before they are compacted. More discussion on this topic will be presented in next chapter.

When water treatment residues are dumped in WTP residual monofills, they will be subjected to cycles of freezing and thawing, and cycles of wetting and drying. Freeze/thaw tests and dry/wet tests were conducted to investigate the properties of the residues under these circumstances. It was observed in both of the tests that all the residue samples had weight loss, volume reduction, and cracking. Cracking usually occurred in the first cycle. The sample became brittle and hard after these tests. It has been observed that water treatment residues have better durability under wetting and drying cycles than under freezing and thawing cycles after comparing the results of the dry/wet and freeze/thaw tests. These properties may influence the operation of WTP residual monofills in the different weather conditions.

The next characteristic to be investigated is strength. Undrained shear strength, friction angle, and cohesion of water treatment residues were determined by direct shear tests and unconfined compression tests. The water treatment residues have largely varying shear strengths. However, the shear strength of the residues is usually low at high water contents. The strength increases when water content is decreased.

There are two types of strength-water content curves observed in the research: one hump type (see Figure 4 in Appendix B) and increasing type (see Figure 5 in Appendix B). From the undrained shear strength of the residue, a determination can be made as to whether the residue can be compacted or not. If so, the type of equipment which can be effectively used to construct the monofill can also be specified. The friction angle and cohesion influence the bearing capacity and slope stability. It was observed that the friction angle and cohesion are controlled by solids content and organic content of the residues.

In this research, consolidation tests were used to investigate the permeability and settlement characteristics. It was noted from the results that the water treatment residues are highly compressible. Values of compression index Cc varied from 0.1 to 4.5, which are very close to those for highly compressible clays. This may due to the high water content and deformation of floc structure of the residues. The swell index values Cs are relatively low, ranging from 0.014 to 0.199. This is because of the thixotropic hardening occurring during unloading and reloading. The water treatment residues usually have low permeability of the order of 10^{-6} to 10^{-7} cm/s due to their fine particle sizes and tightly held floc structure.

CHAPTER 5

CRITERIA PROPOSED FOR DESIGN, CONSTRUCTION, AND OPERATION OF WTP RESIDUAL MONOFILLS

At present, no specific criteria exist for the design, construction and operation of WTP residual monofills. The criteria proposed for design, construction, and operation of WTP residual monofills in this chapter are based on the literature survey and the results of the tests conducted so far. Criteria for MSW landfills have been taken into consideration and relevant information has been extracted from them and included in this report. In such cases, the monofill is either referred to as landfill or waste disposal facility in this report. In cases where the criteria for MSW landfills appears to be too stringent and unrealistic for WTP residual monofills, an attempt has been made to develop a suitable criteria.

The Pennsylvania-American Water Company has a WTP residual monofill at New Castle, Pennsylvania, referred to in this report, as the New Castle site. This monofill has been designed as a class III landfill according to the Regulations of the Pennsylvania Department of Environmental Resources (Penn. DER). A field testing program at the above site is presently underway by the NJIT research team of which the author is a member. Information obtained from the research team's investigations and visits to New Castle site and other utilities has been considered in arriving at the tentative criteria proposed in this report.

5.1 Planning and Site Selection Consideration

Design, construction, and operation a WTP residual monofill is an engineering facility. For this facility to be successfully and efficiently operated, proper planning along with the applications of sound engineering principles is essential in every phase of the project. Most operational problems can be prevented in the initial development stages. This is easier and more economical than correcting the defects after they occur.

5.1.1 Feasibility

The first phase of planning for a WTP landfill project concerns feasibility. It can be safely assumed that monofill disposal of water treatment plant residues is technically and physically practical today. So the question becomes that of the economical and political feasibility of transporting solid wastes to a suitable monofill site and meeting all of the expenses and complying with the stipulations associated with operating the site (National Center for Resource Recovery, Inc. 1974). All disposal options for WTP residue are severely restricted by the environmental regulations and economical consideration.

One important issue that has to be taken into account in the feasibility analysis is public opposition. According to the environmental regulations, public hearings have to be held to address the concerns of the community. Often, the potential developers of landfills will have problems with the site's neighbors. Citizens opposing the location of the landfill will seek to prevent implementation of the project by testifying against the project and the site at public hearings and by filing law suits, directly seeking to overturn or prevent regulatory agency approvals (O'Leary et al. 1986). This is known as the not-in-my-backyard (NIMBY) syndrome.

Factors that affect the economic feasibility of a landfill project are (National Center for Resource Recovery, Inc. 1974):

(1) the availability of a suitable site at reasonable cost,

(2) the volume and composition of the residues,

(3) the distance that residues must be hauled,

(4) the cost of equipment and local labor wage rates,

(5) pre-fill and post-fill steps which must be taken to protect the surrounding environment and to enhance the final usefulness of the site.

Planning process for a new WTP residual monofill, as is the case for MSW landfills, can be divided into the following steps (O'Leary et al. 1986):

1. Establish goals and gather political support,
2. Identify facility design basis and need,
3. Identify potential sites within the region,

4. Select and evaluate in detail the most desirable sites,
5. Select best site for development, and
6. Obtain regulatory approval of site.

5.1.2 Site Selection

Proper selection of a suitable site is essential in order to avoid problems that may occur later. Site selection should consider the local geotechnical, geological, hydrogeological and the climatic conditions. The volume of the water treatment residues expected to be accepted in the monofill, transportation of the residue from the generator to the monofill, and the possible environmental influences are also important factors in site selection (Raghu, et al. 1993).

A properly conducted subsurface exploration program is necessary for site selection. This will consist of a combination of borings, test pits, and other field testing methods, and laboratory tests. These investigations may also include geophysical techniques, if deemed appropriate.

In a site investigation program, the geological features, such as rock outcrops, streams, joints, fractures, and other geomechanical anisotropies of the site have to be mapped and studied. The geotechnical, geohydrological, and seismic characteristics of the site are to be determined. All the aquifers in the site have to be mapped. Groundwater levels and their seasonal fluctuations have to be investigated. Special features of bed rocks such as solutioning due to carbonates and lava tunnels in igneous rocks have to be considered. Suitability of subsurface materials as subbase liner, and for other construction has to be looked into also.

An environmental impact assessment has to be performed soliciting input from local communities and all relevant local, state, and federal agencies.

Effects of constructed facilities on the environment have to be evaluated in the above assessment. To prevent environmental damage, the following site conditions have to be avoided for selection as landfill sites unless the suitability of the site can be adequately demonstrated by the owner/operator of the waste disposal facility (USEPA 1991).

(1) *Airport area*

If a waste disposal facility is located near airport runway, the owner and/or operator of the facility must show that the landfill does not pose a bird hazard to aircraft.

(2) *Wetland*

A landfill should not be located in wetlands unless the owner and/or operator can demonstrate that the proposed facility will not adversely influence the environment, and degrade the wetlands, and an alternative is not practically acceptable, in which case suitable and prescribed mitigatory measures are to be undertaken.

(3) *Fault area*

A waste disposal facility should not be located within 200 feet of a fault that has had displacement in Holocene period (approximately 5000 years ago) unless the owner or operator can prove that a alternative setback distance of less than 200 feet will prevent damage to the structural integrity of the monofill.

(4) *Seismic area*

A landfill should not be located in a seismic zone unless the facility has been designed to resist the 50-year earthquake.

(5) *Floodplains*

If a waste disposal facility is located in a 100 year floodplain, the owner or operator of the facility must demonstrate that the landfill does not restrict the flow of the flood, reduce the temporary water storage capacity of the flood plain, or result in the washout of solid waste so as to pose a hazard to human health and the environment, and result in lost of life and properties.

Another factor that should be taken into account is water table. Even though Penn DER specification for class III landfill used for monofill at New Castle is silent about this issue, author recommends that the bottom of the WTP monofill should be at least two feet above the seasonal high water table in the area.

An ideal landfill will meet the following requirements (Weiss, 1974)

(1) Conforms with land use planning of the area,

(2) Easily accessible in any weather to vehicles expected during the operation of the landfill;

(3) Safeguards against potential surface and ground-water pollution.

5.1.3 Planning Associate With Site Development

In order to ensure that the public has good reason for accepting a new waste disposal facility, adequate engineering planning is required. The first step is to survey proposed sites with the assistance of competent professionals. Evaluation maps should be prepared based on the survey. The type of waste disposal facility best suited for the particular location under examination should be selected. Recommendations should be offered as to construction and location of all-weather access roads. Depths of fill and cut at various locations on the site should be tentatively determined. If on-site materials are not suitable for construction, off site source will have to be considered. By selecting suitable grades and providing culverts and pipes adequately, proper drainage throughout site can be ensured.

Equipment storage buildings, utilities, and water supply for fire and dust control should be planned. A logical sequence of operations should be developed by the engineer before the construction, and updated along with site specifications at various stages of construction. This could be accomplished with the use of bar charts and CPM techniques. Contingency operational plans for equipment for conditions such as those due to weather problems should be prepared.

5.2 Design Considerations

Design and operational activities during development of the landfills are not distinct entities. Basic knowledge and experience in the operational aspects of a general landfill are necessary for the design phase. In essence, the design phase involves development of detailed design specifications for the various components of the monofill such as the liner system, leachate collection system, groundwater monitoring system and closure and post closure operations. Specifications for construction and operations are also developed at this stage. Good design is essential for ensuring the proper service of the monofill, estimating costs, obtaining bids, and operational control and inspection.

5.2.1 Landfilling Methods

There are three major types of landfilling methods, namely excavated trench method, area method, and ramp method, that can be employed in the construction of landfills (National Center for Resource Recovery, Inc. 1974).

Most WTP residues have low solid contents and thus possess low shear strength, as explained in the previous chapter. This would pose problems regarding slope stability, compaction, and constructibility. The author is of the opinion that an area type construction would be preferable for a big monofill having a large surface area and accepting different types of residues with greatly varying components and solids contents.

In the area method (see Figure 6 in Appendix B), a landfill can be divided into two parts: working area and ramp area. Depending on the construction and operation of the ramp area, slope stability may become a factor to contend with. Geotextile liner is placed all around the surface area of the landfill. A leachate or a drainage collection system with a drainage fabric is placed on top of the geotextile. WTP residues are placed on the liner, spread in layers and either compacted as it is or after drying as the case may be. Successive layers are built up until a depth of 10 to 12 feet. The monofill can be divided in cells and operated sequentially. This will be discussed in detail in part 5.4.5 of this report.

In the excavated trench type, the land is excavated and filled in successive parallel trenches alternated by a three to four foot dirt wall (see Figure 7 in Appendix B). Usually, soil from the first trench is used to construct berms for windbreakers to control erosion due to wind and to provide stability to the slopes. As soil is needed to cover a previously opened trench, a new trench is opened. Trenches should be dug at least twice as wide as the tractors which must operate in them. The depth of the trenches varies with soil and groundwater conditions. It is generally eight to ten feet deep. For this kind of construction, the subsurface soil should have good slope stability characteristics.

The ramp method is a variation of the area method. The residues are spread and compacted on a slope. This method has the advantage of obtaining cover materials directly from excavation on the slope and having natural slope to facilitate drainage. Ramp methods can be used for disposing WTP residues with high solids content, which will not pose slope stability problems.

In all these landfilling methods, WTP residues can be mounded, above the existing ground surface. The landfill can then be constructed by dumping the residues above the ground surface. In such cases, the surface drainage and run-off system have to be carefully considered. Subsurface soils have to be evaluated for bearing capacity and settlement due to service and construction loads. Surface mounding is not preferred for WTP monofills with low solids contents due to stability problems. However, for residues with high solids contents, slope stability may not be a serious problem and in that case this method may be economical.

The landfilling method used at the New Castle Disposal Site is area method. Because it is a small WTP monofill, one working surface is adequate for operation. The average waste thickness after closure is five feet. A liner/subbase system of 5 feet of compacted soil with permeability less than 1×10^{-7} cm/sec is provided.(Blazosky, et. al, 1989).

5.2.2 Minimum Solids Contents Requirement for WTP Residual Monofills

Residues to be dumped into monofill have to meet certain requirements like minimum solids contents required. In MSW landfills, waste materials passing paint filter tests are normally accepted. This means that the residues containing free flowing liquids are not accepted for disposal in landfills. For coagulant residues, to pass paint filter test, they should have more than 20-25% solids contents (Cornwell and Kopper. 1990).

In West Germany and Netherlands, a minimum undrained vane shear strength of 208.56 psf (10 KN/m^{2}) is considered appropriate for defining workability and stability of WTP residues. Based on existing literature, the above shear strength is obtained at solids contents of about 25% for WTP residues in the United States. (Cornwall and Kopper, 1990).

Several states in the US have specified different minimum solids contents for WTP residues to be accepted in landfills. Under this circumstance, the author feel that it is very difficult to specify a minimum solids content. It is recommended that if regulations exist for a particular state for minimum solids content, they are to be followed. In the absence of requirements for minimum solids content, it can be stipulated that the residue has to pass the paint filter test.

The actual minimum solid content to be prescribed will depend on the design criteria used for the shear strength of the residue. This in turn is influenced by factors such as landfilling methods, the type of equipments used for monofill operation, the sequence of the monofilling, and climatic conditions. More discussion on this topic is presented under section 5.4.4 of this report.

5.2.3 Liner Systems

Penn DER regulations for class III landfills require a liner system containing a subbase, a soil layer at least two feet with permeability less than 10^{-7} cm/sec, and an impervious flexible membrane (FML) liner not less than 30-milfor Municipal Solid Waste They also require a 1 to 1 ratio of the thickness of the attenuating subbase to the liner (Pennsylvania DER Bulletin, 1992). The author feels that these requirements are too stringent and unrealistic for WTP monofills based on the environmental and geotechnical characteristic of water treatment residue and can be modified appropriately.

WTP residues possess low permeability, typically of the order of 10^{-6} to 10^{-7}cm/sec (Hsieh and Raghu, 1993d). It is believed that the quantity of leachate produced by these residues will be almost insignificant (detailed in part 5.2.4 of this article). More data regarding this matter will be available once the ongoing field tests at the New Castle site are completed. Proper operation can also minimize leachate production.

WTP residues are not toxic and/or hazardous materials. So even if a small amount is leached out of the monofill, adverse environmental effects will not occur. Based on these factors, the author believes that the clay soil liners can be omitted from the liner system of a WTP residual monofill. Other important reason for omitting the soil liner is economic consideration. The soil liner usually takes long time to construct, and consequently the construction costs increase (Raghu, 1993). A typical section of the liner and drainage system is shown in Figure 8 in Appendix B.

A geomembrane is recommended to separate the subbase and WTP residues. And with the technological advances in synthetic geotextiles, the requirement of protection function of a liner system can be safely and economically achieved. The geomembrane also serves to distribute the monofill load more uniformly on the subsurface soils in addition to imparting a reinforcing effect on it.

Some wide and continuous geomembranes with high friction characteristics are commercially manufactured. This means fewer seams will be required resulting in fewer leaks, and less time required for installation. Maintaining a high coefficient of friction along the interface between the geomembrane and other materials is important for stability. This is especially so, if the liner is placed on a steep angle in order to increase the space available for placing residues in a monofill (Woods, 1992). The interface friction is also important for seismic stability of monofills.

Subsurface soil usually can be used as subbase after proper compaction and/or proof rolling. In some instances, such as bad weather conditions, poor subbase conditions, and high permeability due to some aged WTP residues, a soil liner might be necessary. Then the subbase can also act as a liner, provided it has a permeability less than 10^{-7} cm/sec.

The subbase and/or the suggested subbase/liner layer is designed to bear the weight of the solid waste, cover material, other subordinate facilities, and construction loads. It also minimizes settlement of the monofill that may be detrimental to the proper operation of the monofill. This subbase/liner system is also designed to act as a barrier to stop transmission of leachate. A thickness of two feet of compacted soil is considered necessary for this subbase to minimize imperfections of the layer. The subbase/liner system should have a slope of two percent at all points to facilitate easy drainage (USEPA, 1991). If it can be demonstrated as unnecessary by the owner/operator, the permeability requirement for subbase may be waived.

New Castle Disposal site utilizes a subbase/liner system for its monofill. A one-to-one ratio of WTP residue to attenuating soil base (subbase/liner) is used (Blazosky, et.al, 1989).

5.2.4 Leachate Collection Systems

Leachate collection is one of the most important items in the design for municipal solid waste landfill. But for WTP residual monofill, this importance is drastically reduced because insignificant quantities of leachate are produced by the WTP residues in the monofills.

Leachate generation rates are dependent on the amount of liquid the waste originally contained and the quantity of precipitation that enters the landfill through the waste cover or falls directly on the waste. Although the water content of the water treatment residues are usually high, the permeability of the residues are low, being of order 10^{-6} cm/sec. From the table 5.1, it is easy to predict that the leachate passing though the water treatment residues in the monofill be insignificant. Based on this, the leachate collection system of a WTP residual monofill can be omitted

However other factors such as the physical and chemical properties of the residues, local climate conditions, site topography, final landfill cover materials, vegetative covers, etc., also influence leachate generation. Some of the aged residues may act as coarse grained materials due to large particle sizes, while some others may crack extensively after dry and wet and/or freeze and thaw cycles, The permeability of the residues in the monofill will increase under these circumstance. A site located in a area of high precipitation may generate more leachate. In such cases, leachate collection systems are necessary in the WTP monofill.

Table 5.1 Ability of Soil to Transmit Water

Permeability (cm/sec)	Soil type	transmitted water (gal/day/ft^2)
10^2	clean gravel	10^6
10		10^5
1		10^4
10^{-1}	clean sands; mixture of clean	10^3
10^{-2}	sands and gravel	10^2
10^{-3}		10
10^{-4}	fine sands; silts; mixtures of	1
10^{-5}	sand, silt, and clay; glacial	10^{-1}
10^{-6}	fill; Stratified clays; etc.	10^{-2}
10^{-7}	unweathered clay	10^{-3}
10^{-8}		10^{-4}
10^{-9}		10^{-5}

Source: O'Leary P. and Berrin Tansel. 1986. "Leachate Control and Treatment." *J. Waste Age*, 17(5):69.

When leachate collection system is omitted, a drainage system becomes extremely important to a WTP residual monofill. A drainage layer consisting of granular materials and drainage pipes should be designed for this purpose. The liner/subbase should be designed with at least 2% slope in all direction. The slope of the final cover is recommended to be 2%-5%. Run-on run-off system should be carefully designed.

A drainage fabric should be put between the residues and granular drainage layer to prevent residue solids from clogging drainage systems.

New Castle disposal site has omitted leachate system and drainage layer. This may be because the site has a thick (5 feet) attenuating soil subbase/liner constructed in the monofill.

5.2.5 Groundwater Monitoring Systems

Design of groundwater monitoring systems should be based on the site geotechnical and hydro-geological characteristics obtained by subsurface exploration programs. Construction and operation of groundwater monitoring systems are to be considered in the design phase. Information regarding the regime and directions of flow in the vicinity of the landfill is needed for designing a groundwater monitoring system.

In order to obtain background water quality information to assess the performance of the liner, and ensure an early remedy when any damage occurs, a groundwater monitoring system is needed and hence is to be installed in a WTP residual monofill.

A groundwater monitoring system should be located along the boundary of the landfill. Usually at least one well is provided at the upstream end of groundwater flow to obtain background data on water quality. At least, one other well is installed at the downstream end of groundwater flow. Monitoring well placement must be suitable to obtain samples from the uppermost aquifer. Stipulated procedures for sample collection, sample preservation and shipment, and sample analysis should also be included in setting up a ground water monitoring systems. For the detailed design criteria for groundwater monitoring system, USEPA "Draft Technical Manual for Solid Waste Disposal facility Criteria-40 CFR Part 258." can be referred. However, in view of the fact that the probability of contamination due to leachate is very small in a WTP monofill, requirements regarding the number of the wells and the frequency of sampling may not be as stringent as that for MSW landfills.

5.2.6 Final Cover System

A final cover system is designed to minimize infiltration of precipitation and minimize production and migration of gas, enhance stability of the monofill, prevent animals and insect entering residue, control odor, retard the flammability of the waste, and form a good surface drainage layer. (USEPA 1991)

A final cover usually has three layers (see Figure 9 in Appendix B). The top is an erosion layer that is a vegetation/soil cover. The major function of this layer is to control the erosion of the final cover system, and it also improves the appearance of the site by supporting vegetation such as grass on its top. This layer should be stable under freeze/thaw and dry/wet conditions. Since WTP residues are not stable under effects of weather such as freeze-thaw and wet-dry conditions, they can not be utilized as final cover materials.

A granular drainage layer with permeability of $1x10^{-2}$ to $1x10^{-3}$ cm/sec is placed under the erosion layer. Typically, particle sizes of the granular materials should be no coarser than 3/8 inch. These materials should be smooth, and free of debris. Crushed stone is not suitable because an underlying geomemberane may be damaged due to the sharpness of the particles.

Under granular drainage layer, is the infiltration layer. Since the infiltration layer of the final cover is more permeable than the bottom liner system, a bathtub effect may occur, when a landfill fills with liquids. (Austin, 1992). All the three layers of the final cover should have slopes of 2-5 percent to facilitate gravity drainage.

5.2.7 Gas Venting System

Gas venting system is considered unnecessary for lime WTP monofills, since no biogas will be produced by WTP residues based on the discussions in the previous chapter.

5.3 Construction Considerations

A study of the soils and geologic conditions of any area in which a WTP residual monofill may be located is essential to decide as to how it will be constructed and as to how the construction might affect the environment. The study should outline the limitations that soils and geologic conditions impose on safe and efficient construction.

5.3.1 Site preparation

Before any water treatment residues can be dumped on a WTP residual monofill, the site has to be prepared. The entire area of the site should be cleaned and graded as required, roads have to be constructed, and facilities have to be installed.

When a WTP residual monofill needs excavation, open excavation is the major method. The angle of excavated slope depends on types of soil, ground water conditions, and the shear strength of the residues and subsoil. Flattening the slope angle or bench excavation is the most common method used to avoid slope stability problem. Walls or large diameter piling can be used to stabilize slides of relatively small dimension or to retain steep toe slopes so that failure will not extend back into larger mass.

Since WTP monofills will not be constructed in areas where water table is high, dewatering during construction is not expected to be a problem. Open excavation should be kept dry and free from run-off and infiltration. This can be accomplished by providing sumps, in the excavation to collect water and pump it out.

5.3.2 Liner and Cover Systems

In the previous sections, it was pointed out that only under certain circumstances, a soil liner will be required for WTP residual monofill. The infiltration layer acts as a liner as far as permeability is concerned.

The major consideration of the soil liner construction is to achieve permeability less 10^{-7} cm/sec. For this purpose, liner soils should have at least 20 percent of fines (passing no 200 sieve). The types of soil, water content, lift thickness, number of equipment passes will influence the degree and quality of compaction.

Usually, minimum permeability is obtained by compacting the materials to moisture contents 1-7 percent above the optimum water content. The lift thickness and the type of compaction equipment employed will depend upon the type of the material to be compacted. For clayey soils, a lift thickness about 6 to 12 inches is considered most effective. The bonding between lifts is extremely important to prevent leachate flow through the compaction layers. Proper bonding between the lifts can be obtained by kneading or blending a thinner, new lift with the previously compacted lift. This could be accomplished by using a sheep's foot roller that could penetrate the top lift and knead the previous lift. Another method of achieving this is by scarifying and possibly wetting the top inch or so of the last lift placed with a disc, harrow or other similar equipment before placing the next lift (USEPA 1991).

The grade preferred for the cover/liner is about 5% to improve the run-off. Drainage layer should also be compacted to prevent large settlements from occurring. Vibratory rollers are usually utilized for compacting granular materials. Lift height recommended is about 12 inches.

Installation of geomemberane should take into account shrinkage and expansion of the sheeting due to the changes in temperature. Proper shipment and storage of the geomembranes should also be considered. Seaming and performance of the field joints of geomembranes are important factors affecting the function of geomemberanes. Geomembrane should be adequately anchored at the ends. Moreover, geomemberanes are subject to damage from exposure to weather and ultraviolet rays. So they should be covered as soon as possible after installation.

5.3.3. Groundwater Monitoring Systems

Construction of the ground water monitoring well directly affects the quality and representativeness of the samples collected. Installation of ground water monitoring wells is based on the site geotechnical and hydro-geological characterization. A good subsurface exploration program is needed to define the geotechnical and hydro-geological conditions at the monofill site. Monitoring wells must be cased to protect the integrity of the monitoring well borehole. Proper selection of packing materials and good procedures for wells installed can minimize sample turbidity from suspended solids.

5.3.4 Construction and Operation Equipment

Consideration should be given to the fact that it is difficult for some equipment to operate when the WTP residues have low solids contents. Hence, the selection of proper and adequate equipment is a key factor in the efficient construction and operation of a WTP residue monofill. Type, size, and amount of equipment required at a landfill location depend on factors such as the size of the site, the properties of the soil at the site and residues, the quantity of residues handled, the fill method used, etc.

The following machines commonly used for landfilling can fulfill the construction and operation requirements of landfills (Weiss, 1974):

(1) Crawler machines

Crawler machines are of two types: dozer and loader. The crawler dozer is excellent for grading and can be used economically for dozing residues or earth over distances of up to 300 feet. The crawler loader is not efficient in spreading residues, but it is an excellent excavator and can carry soil as much as 300 feet economically.

(2) Rubber-tired machines

Both dozers and loaders are available with rubber-tired wheels. They are generally faster than crawler machines (maximum forward or reverse speed of about 20 mph) but they do not excavate as well.

(3) Landfill Compactors

The landfill compactor is an excellent machine for spreading and compacting on flat or level surfaces. It operates fairly well on moderate slopes, but lacks traction when excavating. Its maximum achievable speed while spreading and compacting on a level surface is about 23 mph, forward and reverse. This makes it faster than a crawler but slower than a rubber-tired machine.

(4) Scrapers

Scrapers are available as self-propelled and towed models having a wide range of capacities. Their prime functions are to excavate, haul, and spread cover material. These earth moving machines can haul cover materials economically long distances (more than 1,000 feet for the self-propelled versions and 300 to 1,000 feet for towed models).

(5) *Draglines*

Large excavations can be made economically with a dragline. Its outstanding characteristic is its ability to dig up moderately hard soils and cast or throw them away from the excavation. This equipment is especially useful for working on WTP residues with low solids content.

5.3.5 Quality Control

During site construction, a quality control program should be followed to assure that the landfill is constructed in accordance with specifications. An inspector should be on site to approve construction work as each phase of construction is completed.

Compaction, permeability, and grain size distribution tests of liner and final cover materials should be conducted. Testing of geomemberanes includes strength test, durability test, chemical resistance test, and onsite test of integrity of the seams of geomemberanes is very important in the laying geomemberane liners (Matrecon, Inc. 1988). Operational records such as, daily records and other documents should be maintained. Any discrepancies in the quality of materials and/or construction will have to be properly resolved.

5.4 Operation Considerations

Operating requirements have been developed to ensure the safe daily operation and management at a landfill. Operating requirements include: residue transportation methods, test data/manifest required by monofill owner or operator, landfilling and compaction methods, winter and wet weather operation, daily cover, run-on/run off control, record keeping, security and access control and maintenance.

5.4.1 Transportation Methods

Haul distance is critical for determining the transportation methods. If a proposed waste disposal site is ten to fifteen miles away from the farthest point of collection, the residues can usually be hauled economically by standard size municipal collection trucks. If the landfill site is twenty or more miles from water treatment plant, one or more transfer stations where residues is loaded into large trailers of 75 cubic yards or more capacity should be taken into consideration. Haul distances of fifty to 100 miles are usually beyond consideration for highway vehicles. In certain instances, hauls which appeared too long are possible using assembled transportation systems, such as rail or barge (Pfeffer, 1992; Wise, 1990).

In transportation during winter, the residues have to be completely covered to prevent odor. (personal communication with the operation staff of Hackensack water treatment Plant, 1993). If possible, some kind of sheet can be provided between the body of the truck and residues to facilitate dumping.

5.4.2 Test Data Requirement

To ensure proper operation, the monofill owner should set up requirements for acceptable residue. WTP residue generator should provide information to demonstrate that their residue meets the requirement for acceptance in the monofill. For this purpose, it is suggested that the following testing data should be provided by the residue generator to the monofill operator for every batch of WTP residues (Raghu, et al, 1993):

1. Solid content and/or paint filter test results,
2. Compaction test results,
3. Shear strength,
4. Permeability,
5. Cation exchange capacity,
6. TCLP, and
7. pH.

Properties of WTP residues are influenced significantly by the solids and chemical contents. Hence, if the results of the TCLP analysis, pH and solid contents/paint filter tests of a certain consignment of residues do not differ significantly from those of the previous batch, results of compaction, permeability, CEC and pH tests may not be provided.

It is important that the designer should provide the necessary information to the operator of the monofill regarding the above items. This will facilitate the monofill operator to make sure that the operation of the facility is in conformance with the conditions assumed for the design and construction. If operating conditions change, the effects of changes have to be properly evaluated immediately. Suitable action has to be taken to correct the situation if conditions should so warrant.

5.4.3 Compaction and Sequence of Landfilling of WTP Residues

Compaction methods used for a WTP residual monofill is essential for prolong the life time of the monofill unit. Factors influencing compaction and landfilling methods are, the size of the monofill, properties of water treatment residues, site geology, local climate condition, and costs for operation.

If the WTP residues have high water contents, it will not be possible to run compaction equipment over the residues. In such a case, the residues will have to be dumped and allowed to air dry. When the solids content of the waste increases by air drying sufficiently to support compaction equipment, the residues can be compacted. The minimum solids content at which the residue will have sufficient strength to support compaction equipment can be estimated. Calculations for determining such a solids content are presented in Appendix C. In practice, the strength of the residues as they are being dried, can be estimated by conducting field tests such as pocket penetrometer tests.

Three basic methods are proposed as below:

(1) Compaction immediately after dumping of residues

When the solids content of all the residues in a WTP residual monofill is sufficient to support compaction equipment, compaction can be performed immediately after the sludge is dumped. Hence the whole operation becomes convenient and economical. This method is suitable for WTP residual monofills of small or medium size that accepts residues with similar environmental and geotechnical properties and fulfilling the requirements specified in Appendix C.

(2) Compaction of residues with low natural solids contents

In this method, a WTP monofill is divided into a number of cells. Water treatment residues are dumped sequentially in the cells for a period of time to be dried. The residues are spread in thin layers and air dried by scarifying it from time to time using discs and tillers. Compaction is performed on the residues when a certain solids content as shown in Appendix C has been achieved after natural drying. If additional batches of residues while compaction is being performed in one cell, these new residues are dumped in an adjacent cell. Here they are followed to air dry after which it can be compacted.

The method discussed here is suitable for monofills of medium to large size. A carefully planned operating procedure is essential for successfully implementing this method. The greatest advantage of this method is that the life of the monofill can be increased, since the volume of the residues is significantly reduced by drying. In regions that experience significant precipitation (snow and/or rainfall), liner and intermediate covers may be required for monofills to control drainage and leachate generation. This will increase the construction and operation costs.

(3) Mixing residues of varying natural solid contents and compacting them

Solid contents of water treatment residues can vary largely. Some of them are fairly high, such as dewatered residues and aged residues while the others may be very low (residues from lagoons and drying beds). It is possible to mix the residues having high solids content with those having low solids content to obtain a solids content or a condition at which the residues could support equipment. Then they can be compacted. The rate and sequence of mixing will have to be determined by trial and error on a case by case basis. Costs incurred in this method may be high due to of the mixing operations involved. But this method can still be economically viable in the view of the total costs.

5.4.4 Winter and Wet Weather operation

A WTP monofill can be operated in the severe winters if good planning and proper operating techniques are followed. For instance, if the trench method is used , the trenches should be excavated before the cold weather sets in. Cover materials should be piled loosely with minimum compaction and covered with straw or leaves in order to prevent erosion and water infiltration.

Wet weather can seriously affect the operations of a sanitary landfill by making the residues too soft, mucky, or slippery for operating equipment. It can also cause serious stability problems. So, it will be difficult to operate WTP residual monofills in the wet weather, especially if the residues are wet.

In a WTP residual monofill, the rate and quantity of wastes delivered are smaller than those for MSW landfills. So both the treatment plant and the monofill operators can plan schedules of delivery of wastes to monofill from the treatment plants suitably to avoid operation during periods of inclement weather.

5.4.5 Daily Cover and Intermediate Cover

Daily cover is necessary for a WTP residue monofill only if odors are produced. Most WTP residues only produce very slight odors. As mentioned earlier, intermediate cover will be required to prevent erosion and water infiltration especially in regions experiencing wet weather. Intermediate covers with thickness of 6 inches are considered adequate for the purpose of the daily cover (Raghu, et. al 1993)

When daily cover is omitted, some kind of preventive measure of soil erosion, such as silt fence should be provided. Penn DER regulations require covering of monofills with an intermediate cover during periods of operational inactivity.

5.4.6 Run-on/Run-off Control

A run-on and run-off system (combined with drainage system) is necessary for a landfill. The system should be designed for the precipitation due to a 24-hour, 25-year recurring storm. Dikes, berms, channels, waterways, terraces, downpipes, and seepage ditches are most frequently used structures for run-on and run-off system. Erosion control measures and proper grading also help in controlling run-on/run-off control.

5.4.7 Record Keeping

A record should be kept of each inspection that is performed on the water treatment residue. The inspection records may include the following information:

(1) The date and time residues were received for inspection,

(2) Source of the residues,

(3) Vehicle and driver identification,

(4) All observations made by the inspector, and

(5) All the testing data required for a batch of residues.

(6) Operation records and groundwater monitoring data.

5.4.8 Closure

All waste disposal facilities have to fulfill closure requirements specified by the relevant local, state and federal regulations. Closure plans and other details will have to be worked out. Final approval from the regulatory agencies will have to be obtained after proper closure. Usually MSW landfills will not be allowed to be disrupted once they are closed. But WTP monofills may be allowed to open so that the residues can be mined and recycled after they dry sufficiently. WTP residual monofill designers and operators will have to consider this issue and discuss this with the regulatory agencies.

5.4.9 Maintenance

Proper maintenance is required during pre-closure and post-closure. Pre-closure maintenance involves maintaining the haul roads in good conditions and keeping them free from odor and dust. At all times, various components of the monofill have to be kept functional.

Post-closure period poses the major concern of maintenance. Usually, post-closure care must be conducted for 30 years (USEPA, 1991). The integrity and effectiveness of any final cover should be maintained. Effects of the settlement, subsidence, erosion, or other events influencing the proper function of the monofill should be corrected.

Ground water should be monitored in accordance with the requirements of the ground water monitoring procedure.

5.4.10 Security and Access Control

The monofill perimeter has to be fenced. Access to the facility should be limited to authorized personnel only. The New Castle Facility has two rows of fences limiting access to site. In the entrance to the facility, signs will have to be posted limiting entry to site. A visitor log book must be maintained in which the names, dates, times and purpose of visits have to be recorded. The site has to be patrolled regularly to prevent acts of vandalism.

5.5 Economic Considerations

The cost of a landfill project can be divided into four parts: initial investment, construction costs, operation costs, and maintenance costs (Hsieh, et al, 1988)

Initial investment is the cost spent from the point of the beginning of the plan of a new landfill to the time the construction permit is received. It includes the following (Walsh, 1990):

(1) Feasibility analysis

(2) Legal services

(3) Financial services

(4) Engineering investigations

(5) Environmental assessments

(6) Engineering design

(7) Land purchase and

(8) Other fees

For this report, the basic data for sanitary landfills from literature has been considered (Walsh, 1990). Author has modified the above costs for the WTP monofills. Total cost for the initial investment is estimated to be about 5-15 percent of the total project costs. The large range of the investment cost is due to the difference in land costs among metropolitan areas and remote areas.

Construction costs usually include site preparation costs, liner/subbase system costs, and costs for installation ground water monitoring system. These costs are about 15-30 percent of the total costs depending on the site conditions and the design of the liner system. In general 40-50 percent of the total costs is for labor, the equipment accounts for 30-40 percent, and the remaining 20 percent is for administration fees and overheads.

Total operation costs are about 40-70 percent of the total project costs. Costs included under this category are:

(1) Transportation from water treatment plant to WTP residual monofill,

(2) Compaction of WTP residue,

(3) Intermediate and daily covers, and

(4) Administration fees and overheads.

Maintenance costs mainly include closure and post closure costs. This cost is about 5-10 percent of the total costs. The major items accounting for maintenance costs are:

(1) Final cover,

(2) Groundwater monitoring,

(3) Maintenance of run-on/run-off system, roadways, structure, and the landfill surface, and

(4) Administration fees and overheads.

CHAPTER 6

SUMMARY AND SUGGESTIONS FOR FUTURE STUDIES

This article is a tentative draft pertaining to the development of criteria for water treatment plant residual monofills. Criteria regarding liners, groundwater and leachate monitoring systems and gas venting systems as applied to MSW landfills is too stringent for WTP residual monofills. Construction and operation criteria revolves around the nature and properties of different types of residues that will be accepted and has been pointed out. Importance of costs, planning and engineering judgment in designing, constructing, and operating monofills has been discussed.

Additional studies are needed to enlarge the data base of information regarding the properties of water treatment residues, and the plan, design, construction, operation, and maintenance of the WTP residual monofills.

Additional laboratory tests may be helpful to understand the environmental and geotechnical properties of the water treatment residues. Basic research should be conducted to develop a theory that can thoroughly explain the characteristics of the residues.

On-site investigations are extremely important to understand the changes in the property of the water treatment residues in the natural environment, especially after dry/wet and freeze/thaw cycles. Leachate generation and odor production should be observed in the field, and compared to the laboratory test results. Data regarding water quality obtained by testing ground water samples should be obtained from the existing WTP residual monofills to assess the environmental effects of the monofill.

Detailed cost estimating should be conducted on the WTP monofills based on actual construction data. Costs for other alternatives of disposal of WTP residues have to be compared with those of monofill to obtain a realistic comparison between various disposal schemes.

APPENDIX A

Table 1 Information Summary of Water Treatment Facilities and Residual Samples

Sample	Residual Type	Name of the Facility	Water Source	
			Type	Name
JCD	Lime	Jersey City Water Treatment Plant at Boonton, New Jersey	Reservoir	Rockaway River and Boonton Reservoir
PVD	Lime	Little Falls Treatment Plant at Clifton, New Jersey	River	Passaic River
WQD	Ferric	Wanaque Water Treatment Plant at Wanaque, New Jersey	Reservoir	Wanaque Reservoir
MWD	Lime	Minneapolis Water Works, Minneapolis, Minnesota	River	Mississippi River
MQD	Alum	Manasquan Water Treatment Plant in Monmouth County, New Jersey	River/Reservoir	Manasquan River and Manasquan Reservoir
HWD	Alum	Haworth Water Treatment Plant at Harrington Park, New Jersey	reservoir	Hackensack River , stored in four reservoirs
NCD	Lime	Ellwood City Treatment Plant in Ellwood City, Pennsylvania	River	Slippery Rock Creek
RWA	Ferric	West River Water Treatment Plant in Woodbridge, Connecticut	Lake	Lake Gaillaud
FLDM	Alum	Bradenton Water Treatment Plant in City of Bradenton, Florida	Lake	Lake Manatee
SLD	Lime	South County Plant in St. Louis, Missouri	River	Mississippi River
SLDF	Same as above	Same as above	Same as above	Same as above

Table 1 Informati n Summary of Water Treatment Facilities and Residual Samples (Continured)

	Impurities in Water Sources (Yearly Average Value) (Yearly Range)							
Sample	Turbidity (NTU)	Color (PCU)	Taste/Odor (Threshold Odor No.)	Iron (ppm)	Manganese (ppm)	Hardness ($CaCO_3$ mg/L)	Trihalomethan e (ppb)	TOC (mg/L)
JCD	1.93 0.5-6	22.08 10-30		0.1	<0.02	68.5 40-70	Not Detected	
PVD	5-75	25-100		1.3	0.11			
WQD	1.33 0.75-2.5	17 0-20		0.103 0.05-0.16	0.045 0.01-0.06	47 170-230		
MWD		43 10-100	<10	0.12 0.05-0.15	<0.01	171 170-230		
MQD	6-300* 2-4**	5-500* 60**		0.7-5.0* 1.0**	0-0.03* <0.13**	60* 30**	100-400* **	
HWD	3	25				120		
NCD	2-100		2	0.5	0.06	150	8.5	
RWA	1.2	26	5	0.15	0.08	25	0-300	3.2
FLDM	1.5-25	176 100-400		0.25		71.9 40-110	400-600	15-25
SLD	21	12		0.169	0.013	167		
SLDF	Same as above	Same as above		Same as above	Same as above	Same as above		

* Manasquuan River; ** Manasquan Reservoir

Note: This information is based on the data provided by individual treatment plants and may not be complete

Table 1 Information Summary of Water Treatment Facilities and Residual Samples (Continured)

	Water Treatment Process and Chemicals Added (Yearly Average Value)				
Sample	Main Water Treatment Processes	Lime (ppm)	Alum (ppm)	Ferric Chloride (ppm)	Coagulant Air and Others
JCD	Aeration, flocculation, sedimentation, filtration, chlorination	1 ppm as softener			Cationic polymer, alum
PVD	Prechlorination, flocculation, sedimentation, multiple media filtration, chlorination		as coagulant		Polymer activated carbon
WQD	Pretreatment, coagulation, sedimentation, filtration, chlorination		Coagulant 10-12 ppm		Polymer, carbon, $KMnO4$
MWD	Lime softening, filtration, carbon adsorption	170 ppm as softener	Coagulant 20 ppm	4 ppm	Polymer activated carbon
MQD	Sedimentation, mixed media filtration, carbon adsorption, chlorination (NaOCl)		Coagulant		Polymer, $KMnO4$, GAC
HWD	Ozone contactor, flotation/skimmer, media filtration, disinfection		5 ppm		Cationic polymer
NCD	Presettling, coagulation, sedimentation, filtration, chloridation	Coagulant		20 ppm	PAC
RWA	Oxidation, flocculation, sedimentation, filtration, chlorination			7.2 ppm	
SLD	Softening, sedimentation, dual medial filtration, disinfection	94 ppm		12.8 ppm (ferric sulfate)	
SLDF	Same as above				

Table 1 Information Summary of Water Treatment Facilities and Residual Samples (Continured)

Sample	Dewatering Process (Solids Content)	Conditioning Agent Added	Aging period for Sample Tested	Properties of Sample Tested		
				pH	Solids Content	Water Content
JCD	Thickener (1.5-2%), filter press (30-40%)	Lime (59%)		12.0	23.3%	329.2%
PVD	Thickener, Filter press (27-30%)	Lime (15%), (polyelectrolyte-occasionally)		12.0	26.2%	281.7%
WQD	Thickener, belt filter press (14%) (being installed). Lagoon (0.5-1.5%), drying bed			6.5	5.4%	549.4%
MWD	Gravity thicker (1-2%), centrifuge (55-60%)			11.0	69.2%	44.5%
MQD	Lagoon, drying bed (30%)		Twelve months	7.8	32.6%	206.7%
HWD	Lagoon, drying bed			6.8	59.7%	67.5%
NCD	Lagoon, drying bed			6.2	39.9%	150.6%
RWA	Lagoon, drying bed		3.5 months	5.3	18.1%	452.5%
FLDM	Lagoon, drying bed			6.4	57.1%	75.1%
SLD	Lagoon		Twelve months	9.1	72.2%	38.5%
SLDF	Lagoon			9.5	38.2%	161.8%

Table 1 Information Summary of Water Treatment Facilities and Residual Samples (Continured)

Sample	Location of Sample Collection	Description of Residual Sample Used for Geotechnical Testing	Sample Collection and Delivery
JCD	Outlet of dewatering machine	Cake form (about 2cm thick), composed of one inner black layer and two outer yellow layers, foul odor	Collected by NJIT research team
PVD	Outlet of dewatering machine	Cake form (about 5cm thick), grey color, with strong foul odor	Collected by NJIT research team
WQD	Drying bed	Paste form, brown and black color, foul odor	Collected by NJIT research team
MWD	Outlet of dewatering machine	Paste form, gray color	Sent by the facility, standing water was observed on top of the container when sample was received
MQD	Drying pile (six month aged)	Lump form, brown, yellow and black color, hard and brittle	Collected by NJIT research team
HWD	Drying bed	Lump form, dark grey color	Collected by NJIT research team
NCD	Drying bed	Lump form, black, brown, and grey color, soft	Sent by the facility
RWA	Drying bed	Paste form, black color, with foul odor	Sent by the facility, standing water was observed on top of the container when sample was received
FLDM	Drying bed prior to landfill	In pieces, coal black color, dry, hard and brittle. Residual material is dark because of high organic content in the raw water.	Sent by the facility
SLD	Landfill (one year aged)	Paste form, greenish grey color	Sent by the facility
SLDF	Lagoon (fresh)	Mud form, greenish grey color	Sent by the facility, standing water was observed on top of the container when sample was received

Table 2 Experimental methods and testing instruments Employed

Test Parameter	Method	Instrument
Geotechnical Test:		
Hydrometer test	ASTM D422	152H-Hydrometer
Liquid limit	ASTM D4318	Liquid Limit Device, CL-205)
Standard proctor test	ASTM D698	Standard Mold and Hammer (CN-415)
Direct shear	ASTM D3080	Direct Shear Device (D-300)
Consolidation	ASTM D2435	Consolidation Device (C-320A)
Unconfined compression	ASTM D2166	Unconfined Compression Device (U-580)
Freeze/Thraw	ASTM D560	Kenmore 64831 Freezer
Wet/Dry	ASTM D559	Blue M Oven
Environmental Test:		
TCLP	EPA 1311	Associated Design and Manufacturing Company, MODEL 3740-6-BRE
Pesticides	EPA 8080	HP 5890 Workstation GC/ECD
BNA	EPA 3510	HP 5890 GC/MS
Metals	Method 200.8	VG Plasma quad ICP/MS
Biodegradation Test		
Biogas Composition		HP 5890 GC/TCD
Microorganisms	EPA 1000	PZEISS Microscopy
Cation Exchange	EPA 9080	Perkin-Elmer AA-305B
Physical Examination	Standard Methods 200	

Table 3 Physical/Chemical Characteristics of Water Treatment Plant Residues

Sample	Iron (%)	Aluminum (%)	Calcium (%)	Sodium (%)	Manganese (%)	Volatile Solids (%)	Fixed Solids (%)	CEC (meq/100g)
JCD	0.06	3.92	12.86	0.14	0.19	34.45	65.55	134.8
PVD	0.04	1.26	17.97	0.15	0.13	9.47	90.53	53.1
WQD	0.60	0.26	0.03	0.12	0.09	39.24	60.76	106.0
MWD	0.042	0.004	0.550	0.024	0.001	15.02	84.98	72.32
MQD	0.051	0.893	0.026	0.106	0.007	3.55	96.45	21.96
HWD	0.006	0.826	0.101	0.006	0.148	14.33	85.67	59.35
NCD	1.172	0.001	2.280	0.174	0.177	17.37	82.63	105.99
RWA	2.125	0.097	1.887	0.263	0.094	38.24	61.76	74.91
FLD	0.162	3.027	0.127	0.043	0.009	61.44	38.56	133.75
FLDM	0.038	0.747	0.125	0.021	0.064	63.41	36.59	50.86
SLD	0.048	0.000	0.509	0.020	0.001	3.62	96.38	55.40

Table 4 TCLP Analyses of Volatile Organic Contents in Water Treatment Plant Residuals

Constituent*	Regulatory (mg/L)	SLD (mg/L)	FLD (mg/L)	MWD (mg/L)	RWA (mg/L)	JCD (mg/L)
Benzene	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Carbontetrachloride	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Chlorobenzene	100.0	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Chloroform	6.0	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
1,2 Dichloroethane	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
1,1 Dichloroethylene	0.7	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Methyl ethyl ketone	200.0	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Tetrachloroethylene	0.7	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Trichloroethylene	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Vinyl chloride	0.2	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010

*All VOCs are determined by TCLP and Purge-trap GC/MS.

Table 4 TCLP Analyses of Volatile Organic Contents in Water Treatment Plant Residuals (continued)

Constituent*	Regulatory (mg/L)	HWD (mg/L)	PVD (mg/L)	MQD (mg/L)	WQD (mg/L)	NCD (mg/L)
Benzene	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Carbontetrachloride	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Chlorobenzene	100.0	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Chloroform	6.0	0.025	0.016	< 0.010	< 0.010	< 0.010
1,2 Dichloroethane	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
1,1 Dichloroethylene	0.7	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Methyl ethyl ketone	200.0	0.012	< 0.010	< 0.010	< 0.010	< 0.010
Tetrachloroethylene	0.7	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Trichloroethylene	0.5	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Vinyl chloride	0.2	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010

*All VOCs are determined by TCLP and Purge-trap GC/MS.

Table 5 Results of TCLP Analyses of Water Treatment Plant Residual Samples

Constituent	Regulatory (mg/L)	JCD	PVD	WQD	MWD	MQD
Arsenic	5.0	<0.069	<0.069	<0.104	<0.104	<0.104
Barium	100.0	<2.566	<2.695	0.727	0.588	1.453
Cadmium	1.0	<0.052	<0.052	<0.020	<0.020	0.092
Chromium	5.0	<0.112	<0.618	0.078	<0.048	0.062
Lead	5.0	<0.034	<0.034	<0.062	<0.062	<0.062
Mercury	0.2	<0.020	<0.020	<0.019	<0.019	<0.019
Selenium	1.0	<0.137	<0.137	<0.189	<0.189	<0.189
Silver	5.0	<0.069	<0.069	<0.007	<0.007	<0.007
Chlordane	0.03	ND	ND	<0.001	<0.001	<0.001
Endrin	0.02	ND	ND	<0.001	<0.001	<0.001
Heptachlor	0.008	ND	ND	<0.001	<0.001	<0.001
Heptachlor expoxide	0.008	ND	ND	<0.001	<0.001	<0.001
Lindane	0.4	ND	ND	<0.001	<0.001	<0.001
Methoxyclor	10.0	ND	ND	<0.001	<0.001	<0.001
Toxaphene	0.5	ND	ND	<0.001	<0.001	<0.001
2, 4 D	10.0	ND	ND	<0.001	<0.001	0.001
2, 4, 5 TP	1.0	ND	ND	<0.001	<0.001	<0.001

Table 5 Results of TCLP Analyses of Water Treatment Plant Residual Samples

Constituent	Regulatory (mg/L)	HWD	NCD	RWA	FLDM	SLD
Arsenic	5.0	0.145	<0.104	<0.104	0.145	<0.104
Barium	100.0	2.285	3.400	7.370	0.796	2.640
Cadmium	1.0	0.081	<0.020	<0.020	0.043	<0.020
Chromium	5.0	0.272	0.044	0.100	0.075	0.288
Lead	5.0	<0.001	0.311	0.284	0.147	0.144
Mercury	0.2	<0.019	<0.019	<0.019	<0.019	<0.019
Selenium	1.0	<0.023	<0.189	<0.189	<0.023	<0.189
Silver	5.0	<0.072	<0.007	<0.007	<0.072	<0.007
Chlordane	0.03	<0.0005	<0.0005	<0.001	<0.0005	<0.001
Endrin	0.02	<0.0001	<0.0001	<0.001	<0.0001	<0.001
Heptachlor	0.008	<0.0001	<0.0001	<0.001	<0.0001	<0.001
Heptachlor expoxide	0.008	<0.0001	<0.0001	<0.001	<0.0001	<0.001
Lindane	0.4	<0.0001	<0.0001	<0.001	<0.0001	<0.001
Methoxyclor	10.0	<0.0005	<0.0005	<0.001	<0.0005	<0.001
Toxaphene	0.5	<0.0001	<0.0001	<0.001	<0.0001	<0.001
2, 4 D	10.0	<0.0005	<0.0005	<0.001	<0.0005	<0.001
2, 4, 5 TP	1.0	<0.0001	<0.0001	<0.001	<0.0001	<0.001

APPENDIX B

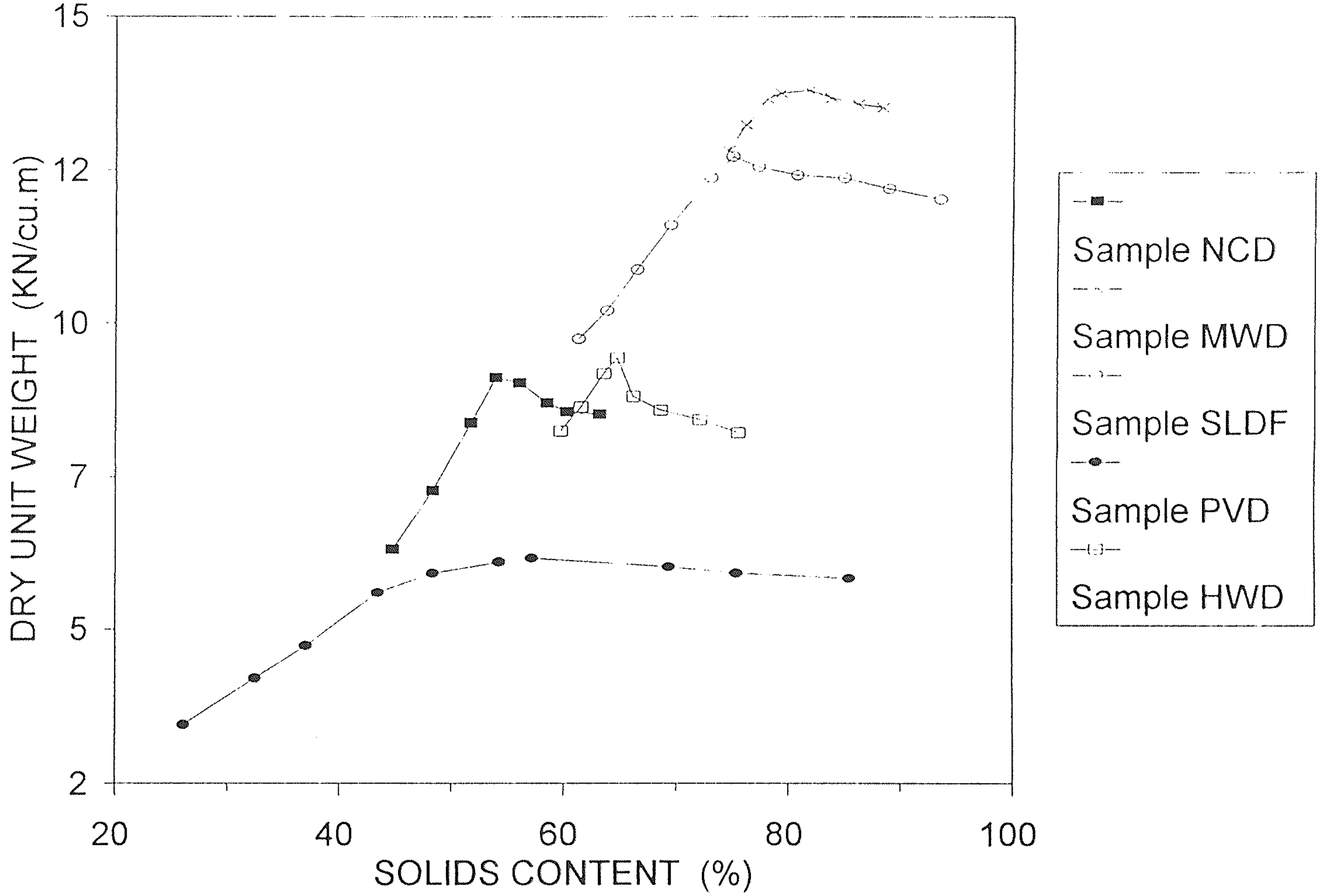

Figure 1. Compaction Curves of WTP Residual Samples from Wet Side with One Hump Pattern

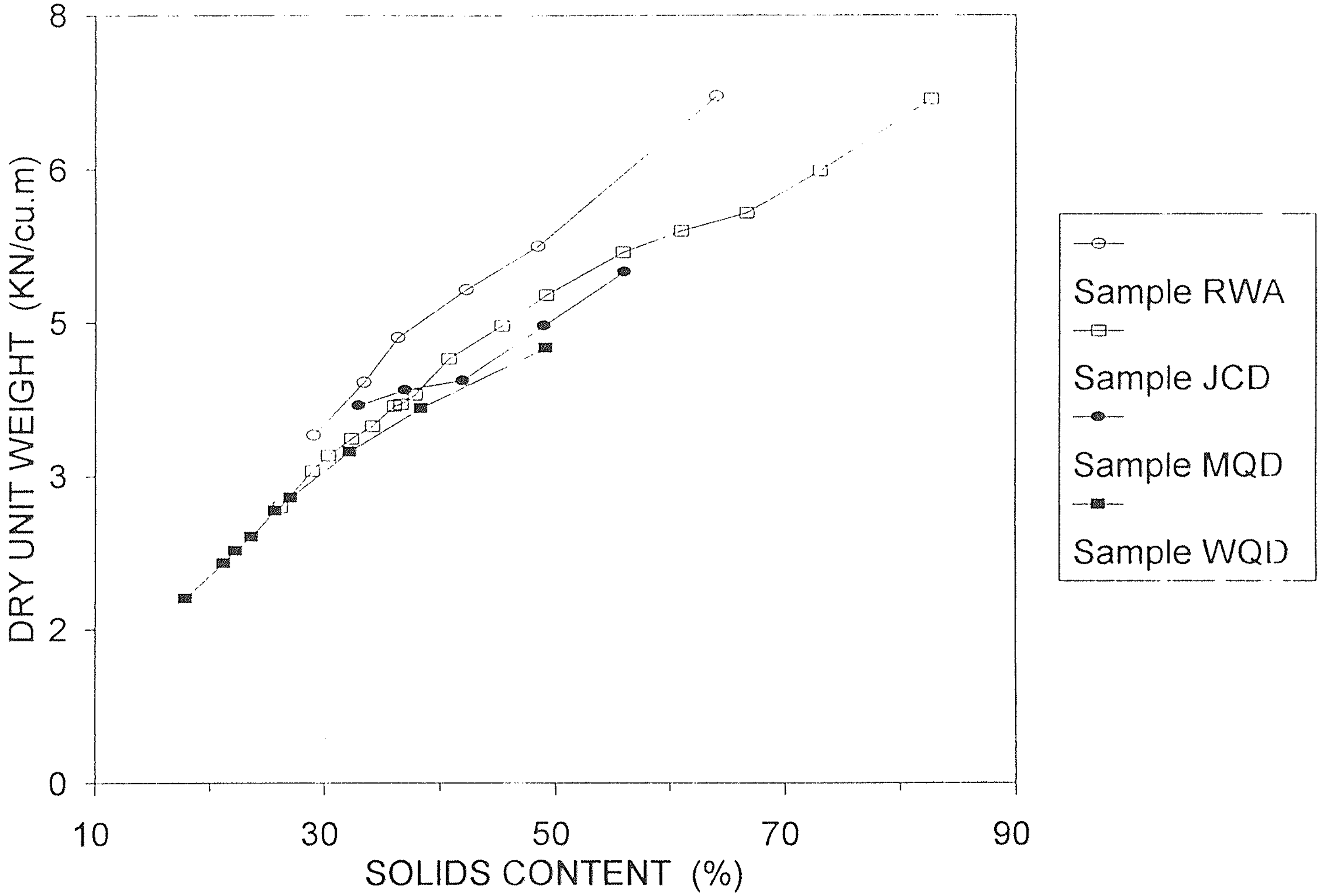

Figure 2. Compaction Curves of WTP Residual Samples
from Wet Side with Increasing Pattern

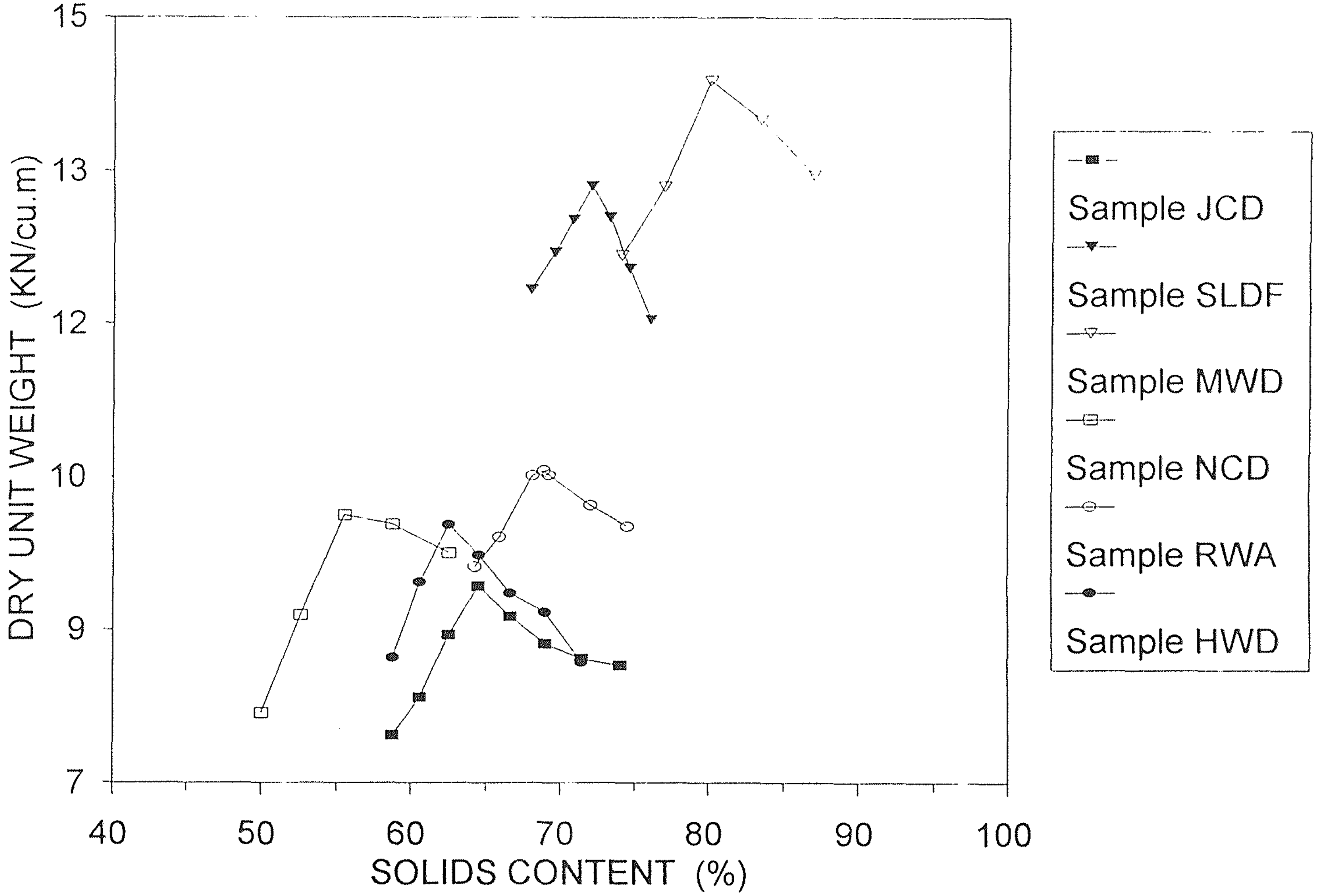

Figure 3. Compaction Curves of WTP Residual Samples from Dry Side

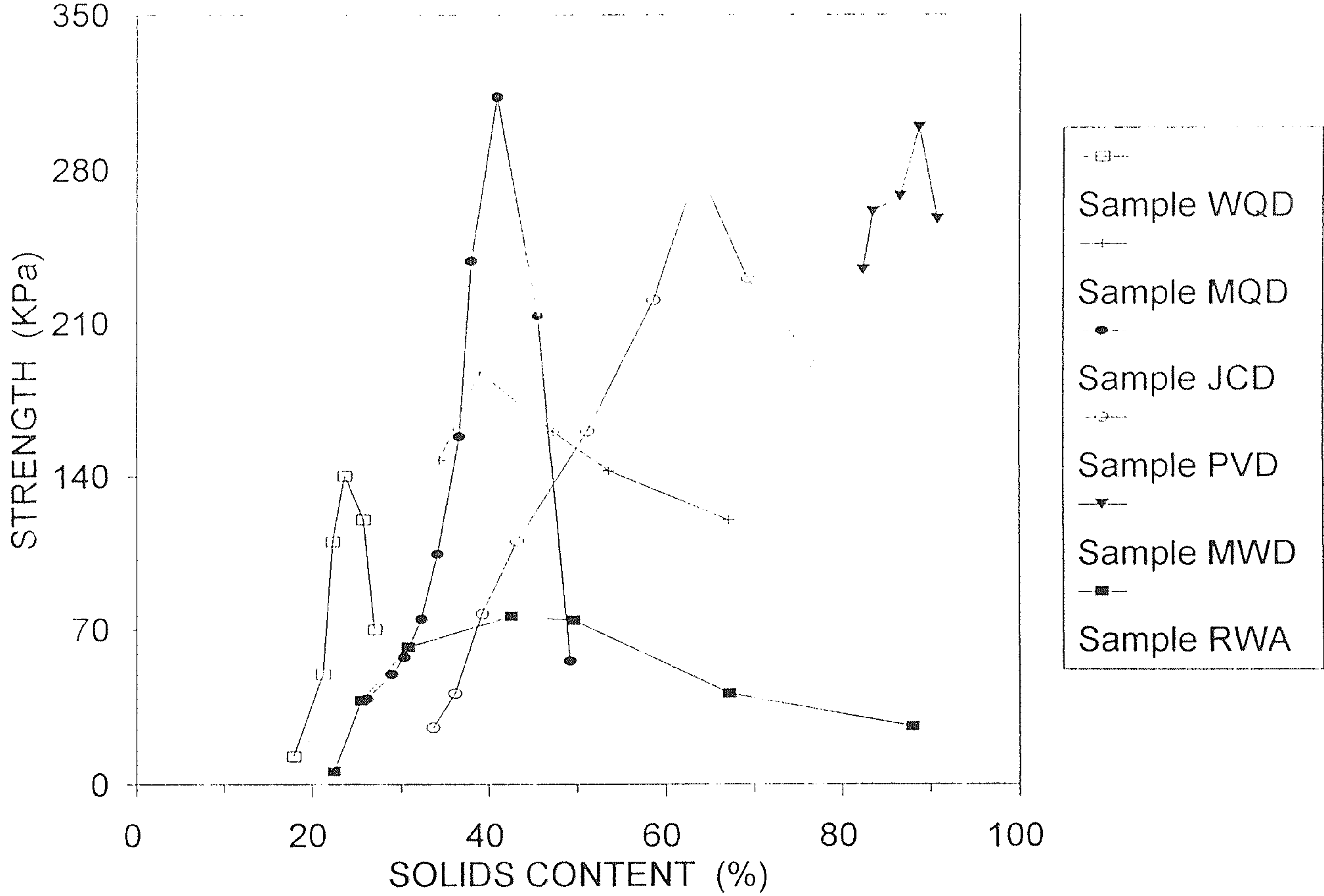

Figure 4. Strength vs. Solids Content Curves of Unconfined Compression Tests with One Hump Pattern of WTP Residual Samples

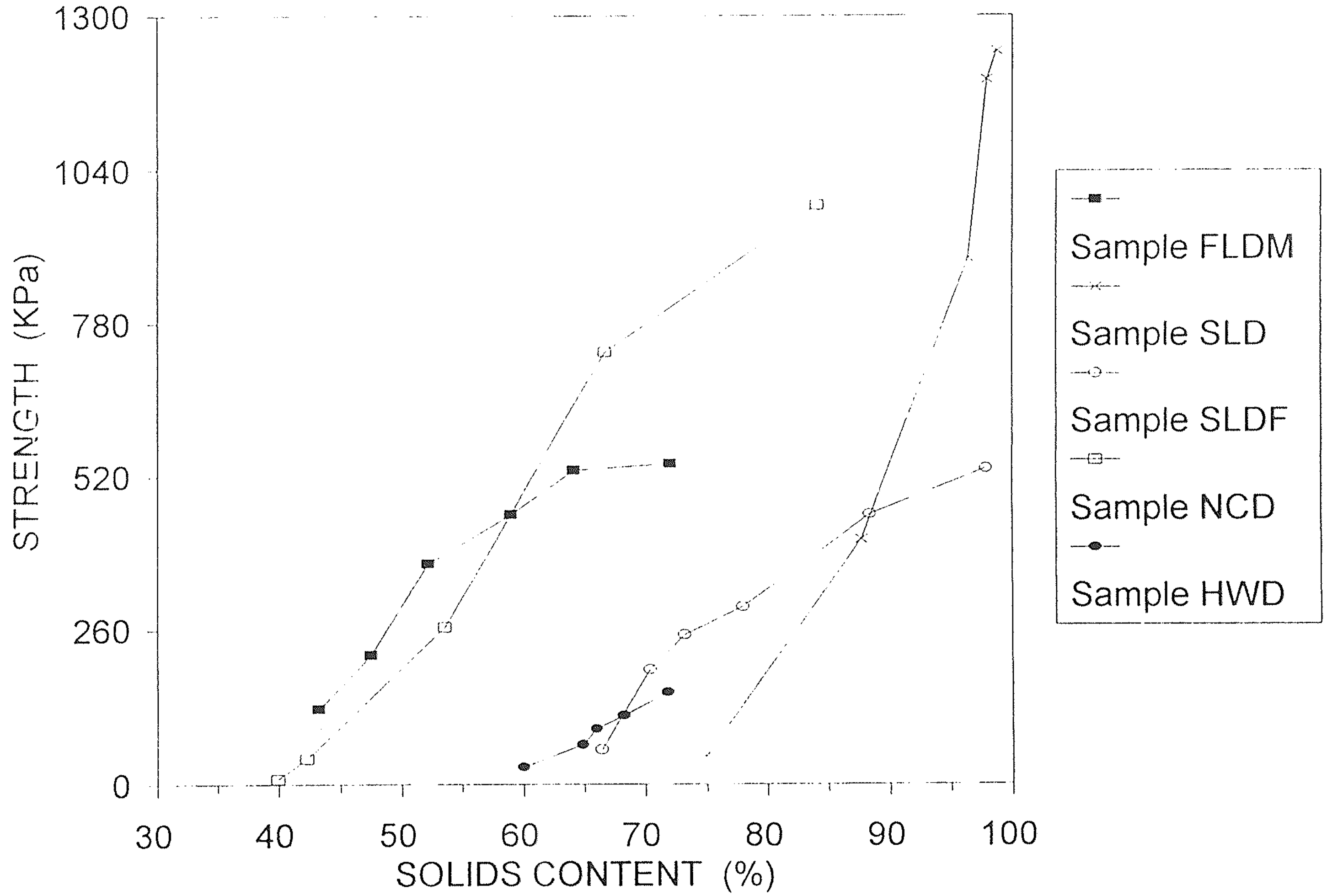

Figure 5. Strength vs. Solids Content Curves of Unconfined Compression Tests with Increasing Pattern of WTP Residual Samples

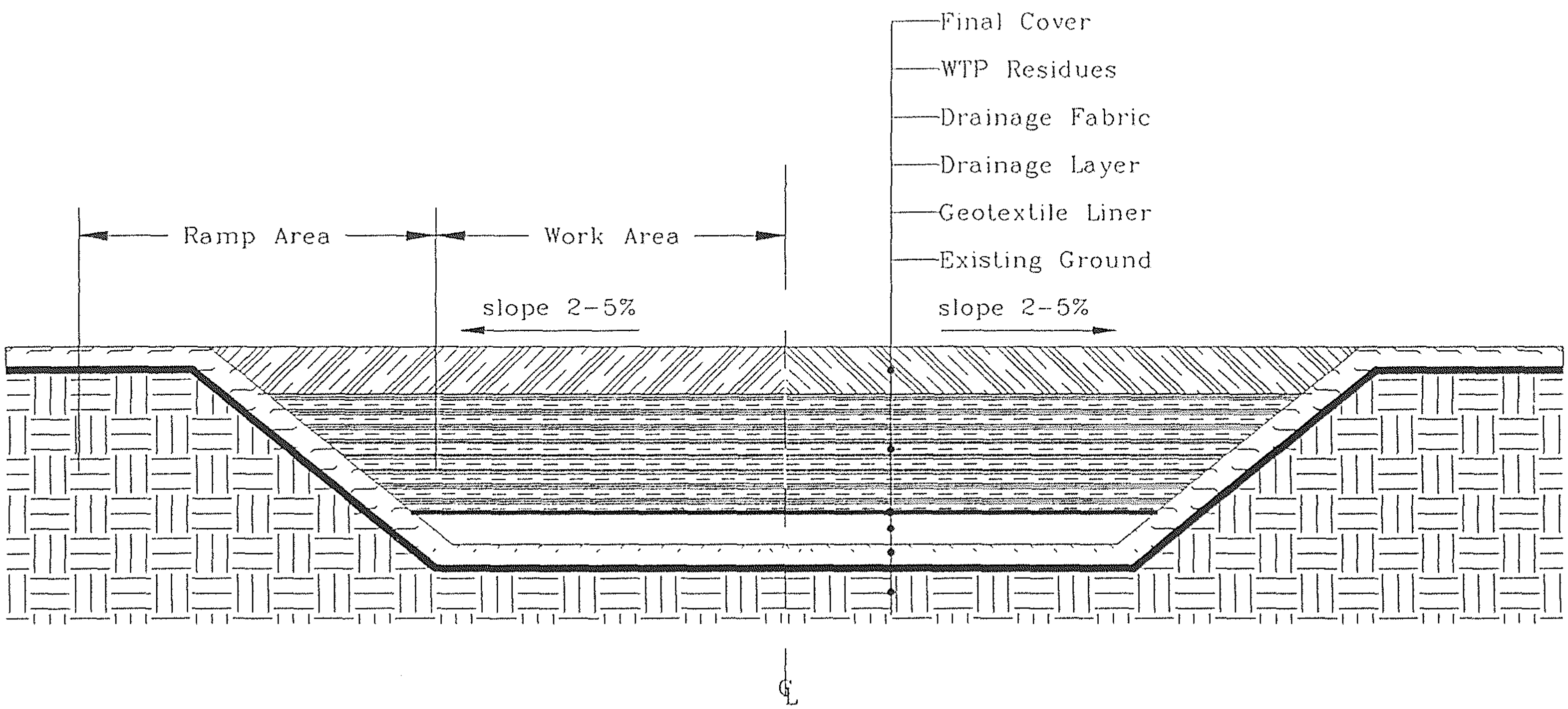

Figure 6 Area Method of Landfilling

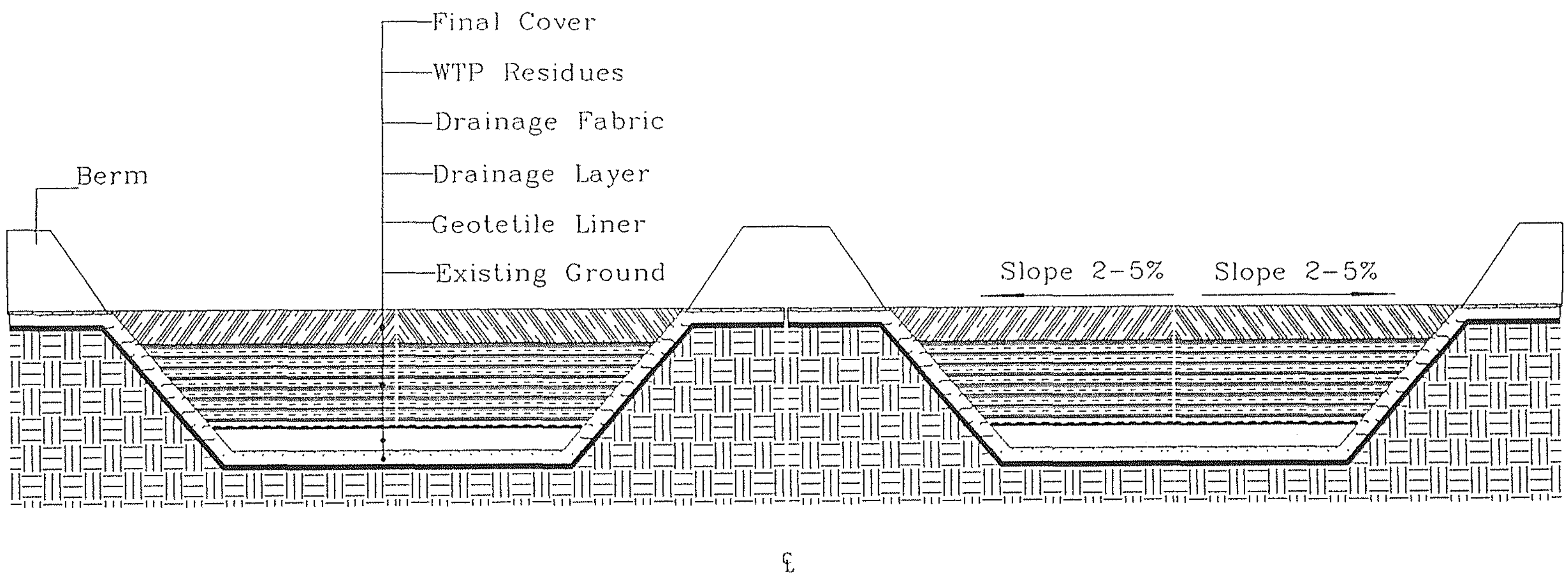

Figure 7 Excavated Trench Method of Landfilling

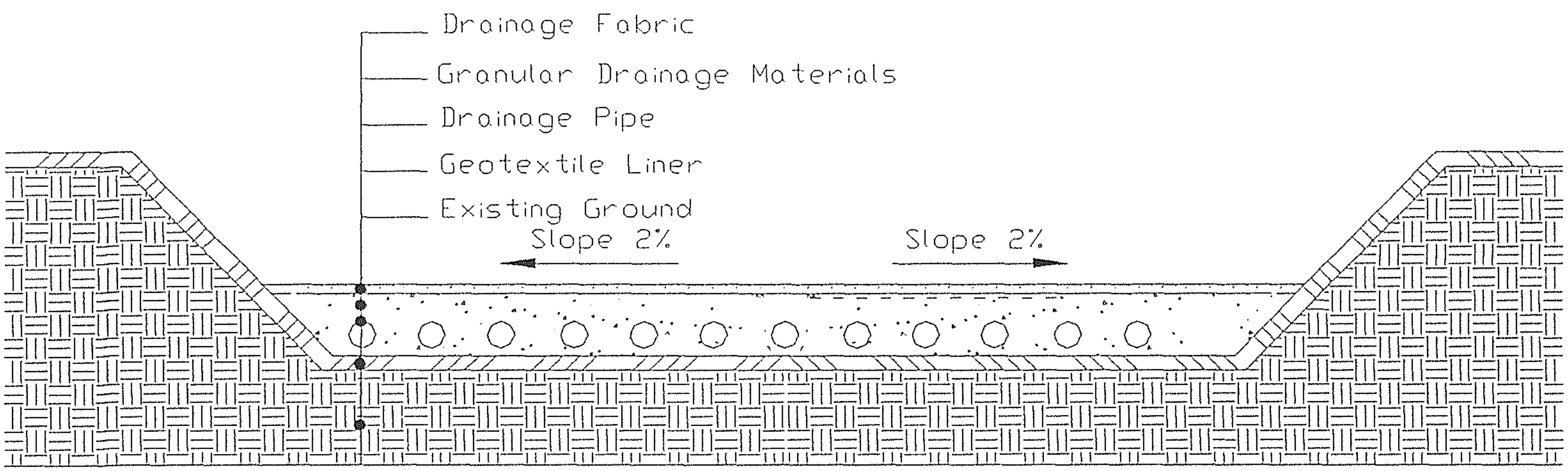

Figure 8 Liner System and Drainage System

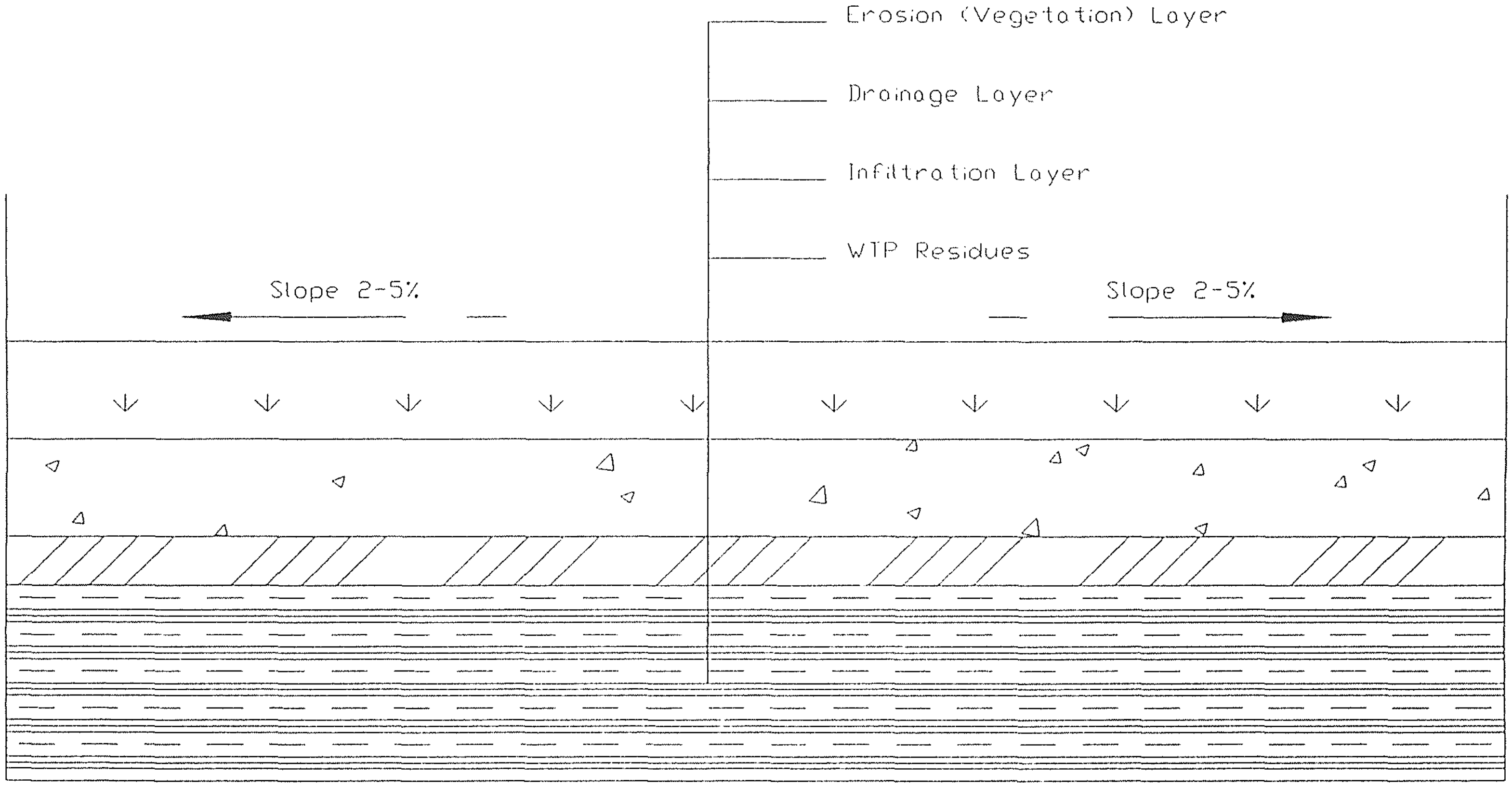

Figure 9 Final Cover

APPENDIX C

APPENDIX C

Calculation of Minimum Solids Content of WTP Residues to Support Compaction Equipment

Assume the tire pressure of compaction equipment to be 50 psi. The relationship between the tire pressure and unconfined compression strength is given below for a plane strain condition involving strip loads (Chen el. al, 1988):

$$p = (2 + \pi)\ K\ b \qquad (1)$$

Where,

P is the load due to equipment per unit length,

K is equal to q_u,

q_u is unconfined compression strength of WTP residue,

b is the width/diameter of the wheel.

Since this is an undrained condition and the loading is only temporary (construction loading), a factor of safety 2 is considered to be adequate. So equation (1) can be modified to equation (2) below:

$$F * P/b = (2 + \pi)\ q_u \qquad (2)$$

Where F is factor safety, wheel pressure is equal to P/b. Substituting F = 2, and P/b = 50 psi in equation (2):

$$(2) \times (50) = (2 + 3.14)\ q_u$$

$$q_u = 19.46 \text{ psi } (134.33\ KN/m^2)$$

The solids contents of the different WTP residues tested for this project, at which the unconfined compression strength is 19.46 psi (134.33 KN/m^2), can be determined from Figure 5. Results of these calculations, yielding the value of minimum solids contents of WTP residues required to support compaction equipment, are provided below:

Type of Residue*	JCD	PVD	WQD	MWD	MQD
Solids Content (%)	35	82	23	47	33
Type of Residue*	**HWD**	**NCD**	**FLDM**	**SLD**	**SLDF**
Solids Content (%)	70	47	43	78	67

* For explanation of symbols like JCD, please refer to Table 1.

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